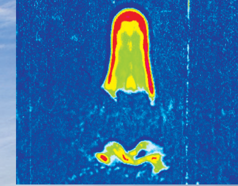
LOS ALAMOS SCIENCE AND TECHNOLOGY MAGAZINE

JANUARY 2012



1663

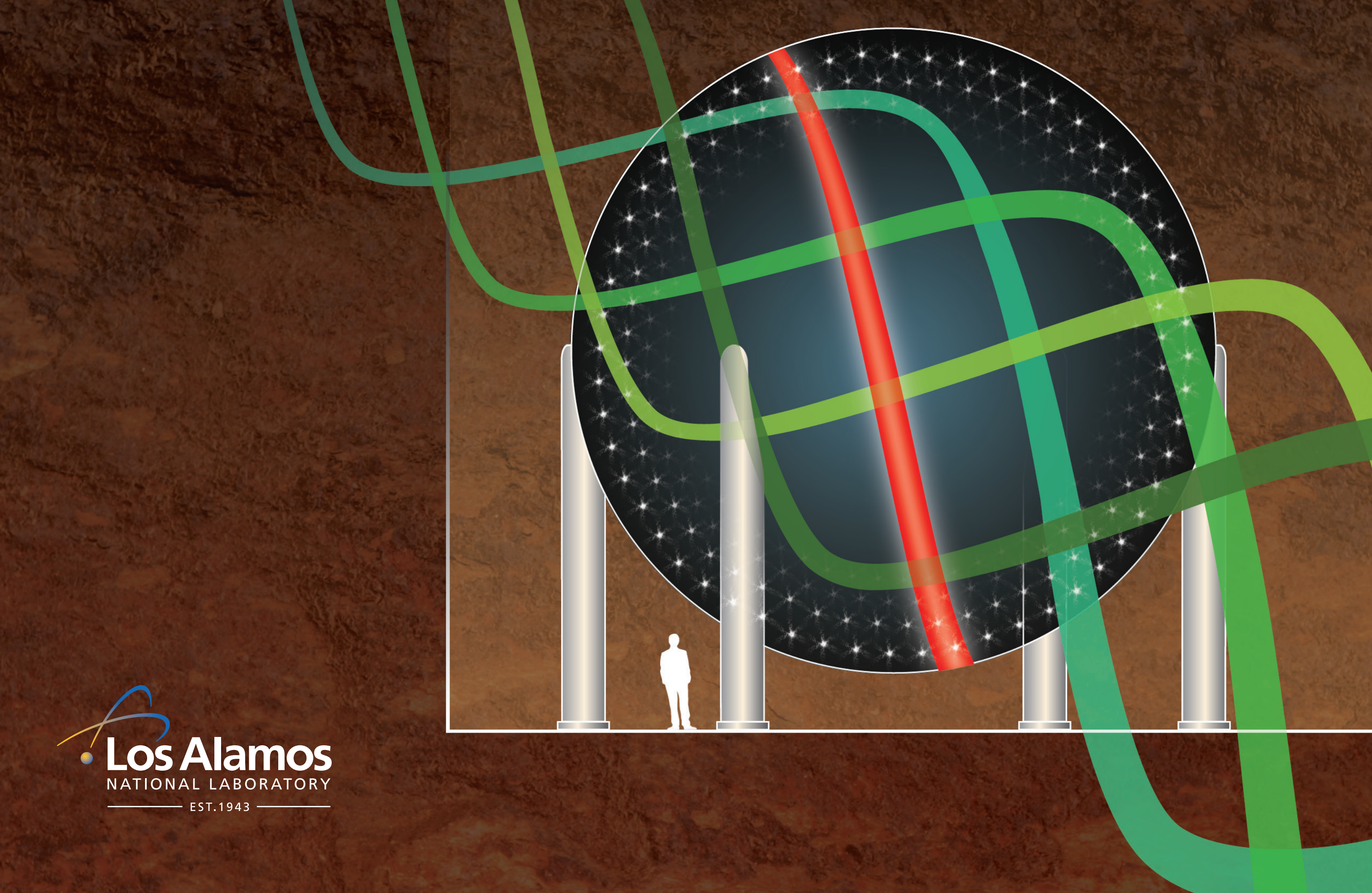
New Neutrinos

Algal Biofuels

Charged-Particle Vision

Primordial Soup

A NEW FLAVOR OF MATTER?



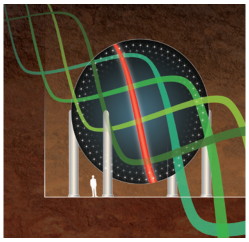
Los Alamos
NATIONAL LABORATORY
EST. 1943

1663

LOS ALAMOS SCIENCE AND TECHNOLOGY MAGAZINE

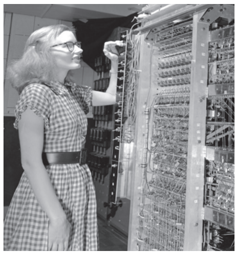
About Our Name: During World War II, all that the outside world knew of Los Alamos and its top-secret laboratory was the mailing address—P. O. Box 1663, Santa Fe, New Mexico. That box number, still part of our address, symbolizes our historic role in the nation's service.

About the LDRD Logo: Laboratory Directed Research and Development (LDRD) is a competitive, internal program by which Los Alamos National Laboratory is authorized by Congress to invest in research and development that is both highly innovative and vital to our national interests. Whenever *1663* reports on research that received support from LDRD, this logo appears at the end of the article.



About the Cover: Beneath the grounds of the Fermi National Accelerator Laboratory in Illinois, a beam of neutrino particles streams through the MiniBooNE detector. This experiment tests the degree to which neutrinos shift from one "flavor" to another. Each neutrino normally travels as a mixture of flavors—called electron, muon, and tau—with the relative contribution from each flavor oscillating in time as a wave. While three different flavors (shades of green) are well established in particle physics, recent results appear to confirm an earlier finding from Los Alamos, suggesting a hidden, fourth flavor of matter (red). These MiniBooNE results may substantiate the rare discovery of a new phenomenon in physics.

Then and Now



Top: MANIAC, the first computer at Los Alamos (1952).

Middle: Cray 1, the Laboratory's first supercomputer (1976).

Bottom: Cielo, the leading supercomputer in the Laboratory today (ranked #6 in the world).

Right: A simulation of a foam material being crushed under a gravitational load, projected in an immersive display room known as the CAVE (Cave Automatic Virtual Environment). The coloring indicates stress in the material (magenta is greatest).

Computing

Computers have played an important role at the Laboratory since it was founded in 1943. The wartime staff used hand-operated slide rules and adding machines, but by the early 1950s, the Laboratory had built one of the world's first electronic digital computers. Called the MANIAC (mathematical analyzer, numerical integrator, and computer), it was used to carry out calculations necessary for hydrogen bomb research as well as studies of thermodynamics, simulations using the Monte Carlo method, and attempts to decode DNA. In the following years, the Laboratory developed computers cooperatively with corporate partners such as IBM, Control Data Corporation, and Cray Research. The Cray 1, completed in 1976, is often regarded as the world's first modern supercomputer.

Throughout the 1980s and 90s, Los Alamos played an important role developing major computing advances, such as parallel processing and cluster architecture. In 2008, its Roadrunner computer became the first to break the petaflop barrier—one quadrillion floating-point operations per second—enabling scientists to accurately model a vast array of complex phenomena including nuclear tests, pandemics, supernovae, and climate change. Last year, another petascale computer arrived at Los Alamos. Named Cielo (Spanish for sky), it will run some of the largest and most demanding workloads in modeling- and simulation-based science. Among supercomputers, Cielo currently ranks sixth in the world and Roadrunner ranks tenth.

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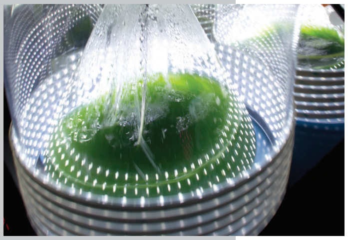
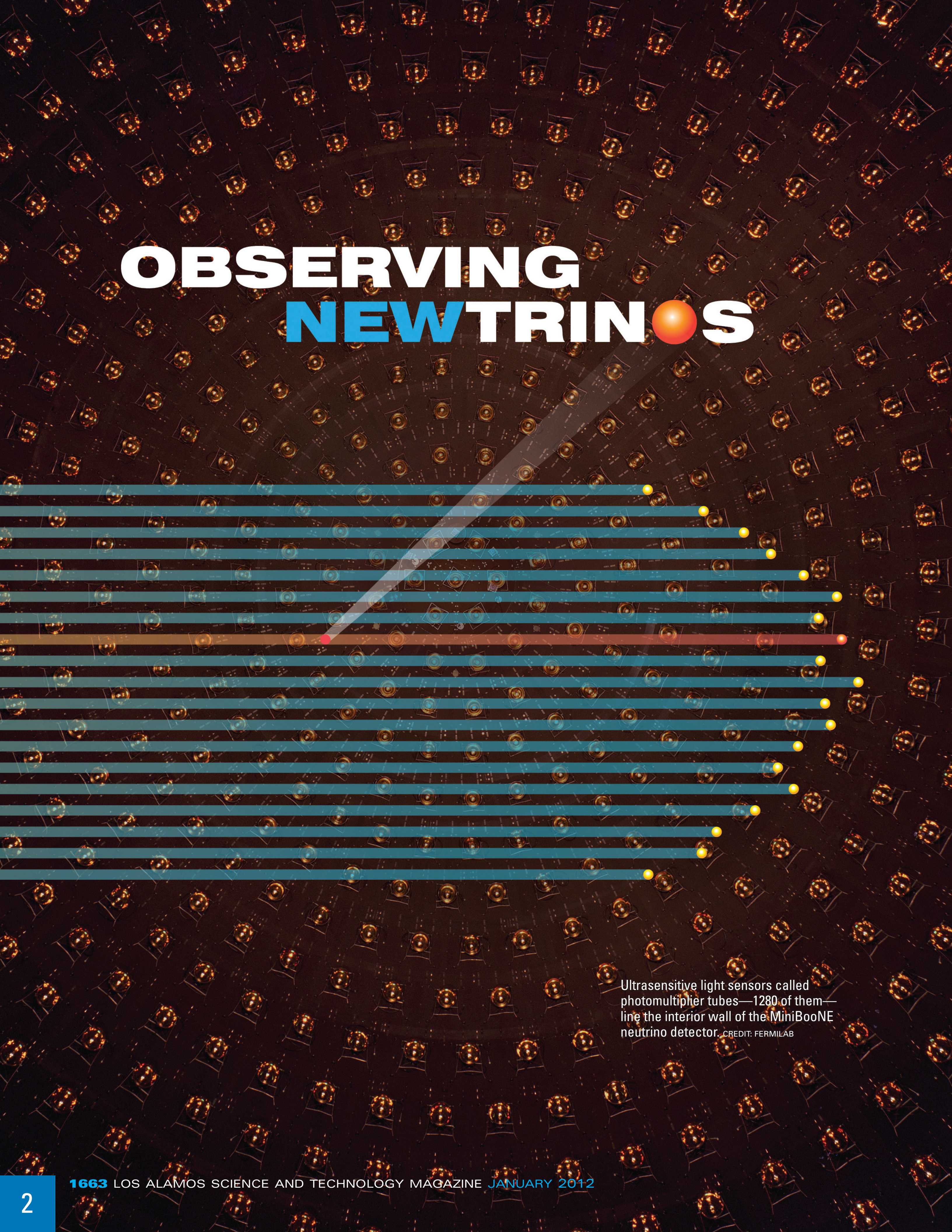


SPOTLIGHT

OBSERVING NEWTRINOS



Ultrasensitive light sensors called photomultiplier tubes—1280 of them—line the interior wall of the MiniBooNE neutrino detector. CREDIT: FERMILAB

The field of particle physics spent much of the last century converging on the "standard model" that describes subatomic particles and the forces by which they interact. Ambitious research that began in the early 1900s with hot-air balloon experiments aimed at catching cosmic rays, and followed later in the century with accelerator-based experiments, led to the extraordinary success of the standard model. Nonetheless, the excitement in particle physics often lies not with the vast body of solidly established textbook knowledge, but rather on the fringe, where researchers seek to identify new physics beyond the standard model. Some even hope to find a problem with the model, in order to spur an intellectual expedition into the unknown. And mounting evidence indicates they may finally get that chance.

Exploring the fringe is hard to do, often requiring more money for bigger accelerators in order to probe energy scales that would otherwise remain just out of reach. But sometimes you get lucky: an unexpected quirk could reveal itself in a more mainstream experiment. That's what happened in 1995 when results from Los Alamos's Liquid Scintillator Neutrino Detector (LSND) were released. The results hinted at the existence of a new particle, and in so doing, defied elements of the standard model that had already seemed established through other experiments. As the scientific method demands, the unexpected results were intensively scrutinized—even criticized—and now duplicated. The MiniBooNE collaboration (Mini Booster Neutrino Experiment), located at the Fermi National Accelerator Laboratory in Illinois, has accumulated enough data to shed some light on the anomaly. And their results are consistent with LSND.

Photomultiplier tube. CREDIT: FERMILAB

Both LSND and MiniBooNE are detectors for subatomic particles called neutrinos. To appreciate their experimental results, it is useful to examine how neutrinos fit in among the other elementary particles. The standard model identifies two categories of matter particles: quarks and leptons. Protons and neutrons, which live inside atomic nuclei, are made from quarks and therefore interact with other matter particles the way quarks do; that is, they interact via electromagnetic forces, strong nuclear forces, and weak nuclear forces. (They also interact gravitationally, as all matter and energy does, but gravity is far too weak at the individual particle level to have any measurable effect in particle physics experiments.)

Leptons behave somewhat differently. They do not experience the strong nuclear force and therefore cannot be bound inside atomic nuclei. Some leptons, like the electron, are electrically charged and therefore interact electromagnetically. But neutrinos are uncharged leptons. They experience only the weak nuclear force, and that force is, as its name indicates, quite weak. As a result, neutrinos rarely interact with other particles. Nearly 100 trillion neutrinos originating in the Sun pass straight though each person on Earth every second, and statistically, only one of these solar neutrinos will interact with any subatomic particle in that person's body during his or her entire life. And it's not just the human body; neutrinos rarely interact with anything, including neutrino detectors, making neutrino research very challenging. (Neutrinos might never have been discovered at all, except that some energy seemed to go missing whenever a neutrons decayed into lighter particles, and to conserve total energy, it seemed reasonable to hypothesize the existence of phantom particles that take the missing energy away with them in order to ensure that total energy is conserved. Neutrinos remained hypothetical for two decades until they were detected experimentally in the 1950s by Los Alamos researchers Fred Reines and Clyde Cowan; Reines lived to receive the 1995 Nobel Prize as a result.)

To Catch a Neutrino

Catching a neutrino interacting with some other particle by the weak nuclear force is difficult, but not impossible. One needs a very large number of neutrinos in a very large detector in order to catch one neutrino interacting amidst countless trillions that cross the detector unnoticed.

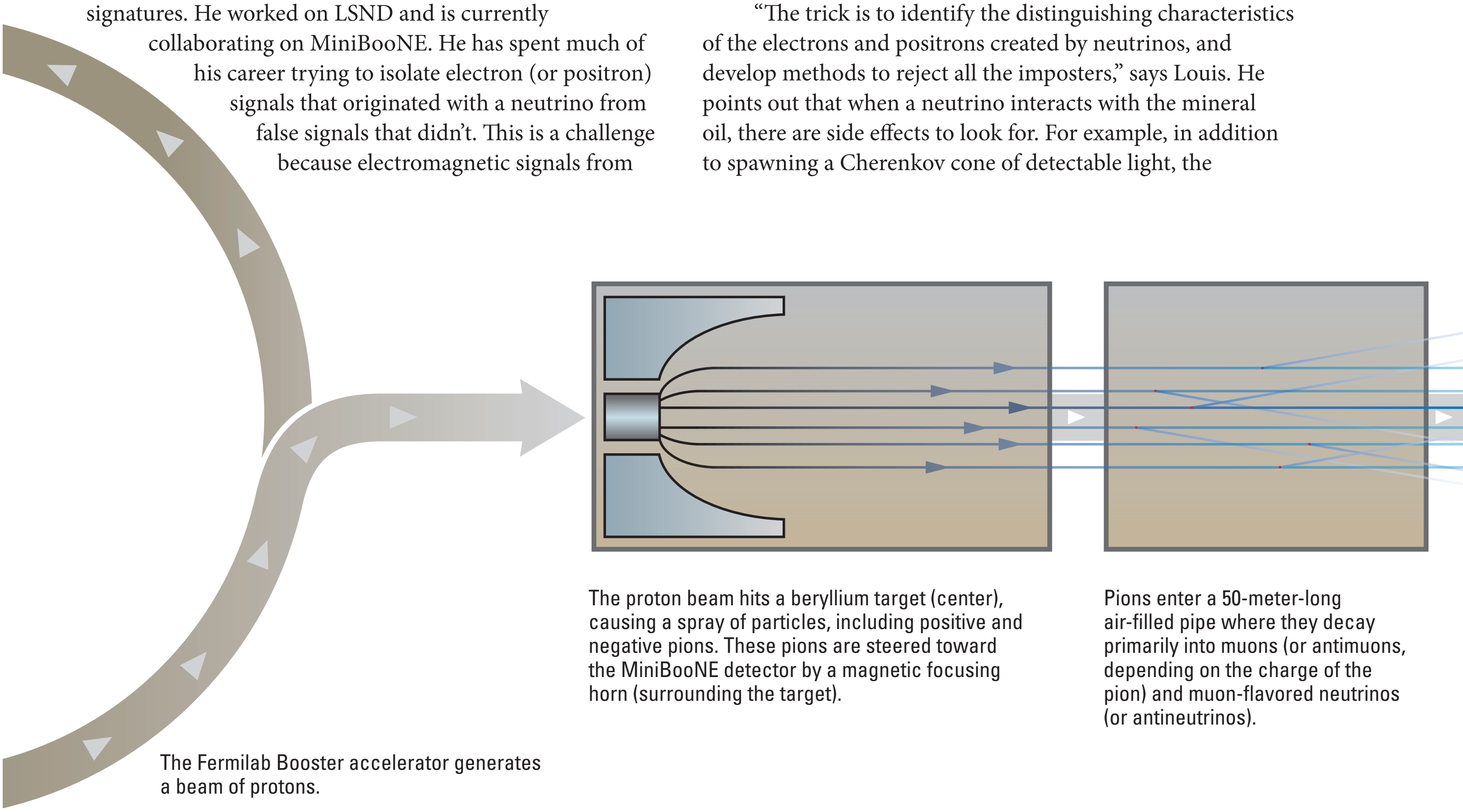
In addition, the neutrino interaction must be inferred. When a neutrino collides with another matter particle, the collision can create a charged particle—usually either an electron or its antimatter twin, a positron. That electron (or positron), not the neutrino itself, is what produces a detectable signal.

The MiniBooNE detector is a massive, spherical tank filled with 250,000 gallons of clear mineral oil. Nearly 1300 extremely sensitive light sensors, called photomultiplier tubes (PMTs), line the interior wall. When a neutrino interaction within the mineral oil causes an electron to zoom through the detector, that electron travels faster through the mineral oil than light would. (Nothing travels faster than light in vacuum—but through a medium like air, water, or mineral oil, this is possible.) Crossing the light-speed barrier in a medium is like crossing the sound-speed barrier, triggering the optical equivalent of a sonic boom. This is known as the Cherenkov effect. A forward-directed flash of visible light spreads out in an expanding cone until it reaches the PMTs, where it is recorded. In this way, MiniBooNE detects a neutrino.

The 12-meter-diameter MiniBooNE detector (seen here through a fish-eye lens) is located underground to shield it from cosmic rays, which could create false detection signals.
CREDIT: CARY KENDZIORA, FERMILAB

Bill Louis is a physicist at the Los Alamos National Laboratory and a pioneer in the search for neutrino signatures. He worked on LSND and is currently collaborating on MiniBooNE. He has spent much of his career trying to isolate electron (or positron) signals that originated with a neutrino from false signals that didn't. This is a challenge because electromagnetic signals from other electrons, or even from photons (particles of light), arise frequently and can easily mimic a neutrino-induced electron.

"The trick is to identify the distinguishing characteristics of the electrons and positrons created by neutrinos, and develop methods to reject all the imposters," says Louis. He points out that when a neutrino interacts with the mineral oil, there are side effects to look for. For example, in addition to spawning a Cherenkov cone of detectable light, the



The Fermilab Booster accelerator generates a beam of protons.

The proton beam hits a beryllium target (center), causing a spray of particles, including positive and negative pions. These pions are steered toward the MiniBooNE detector by a magnetic focusing horn (surrounding the target).

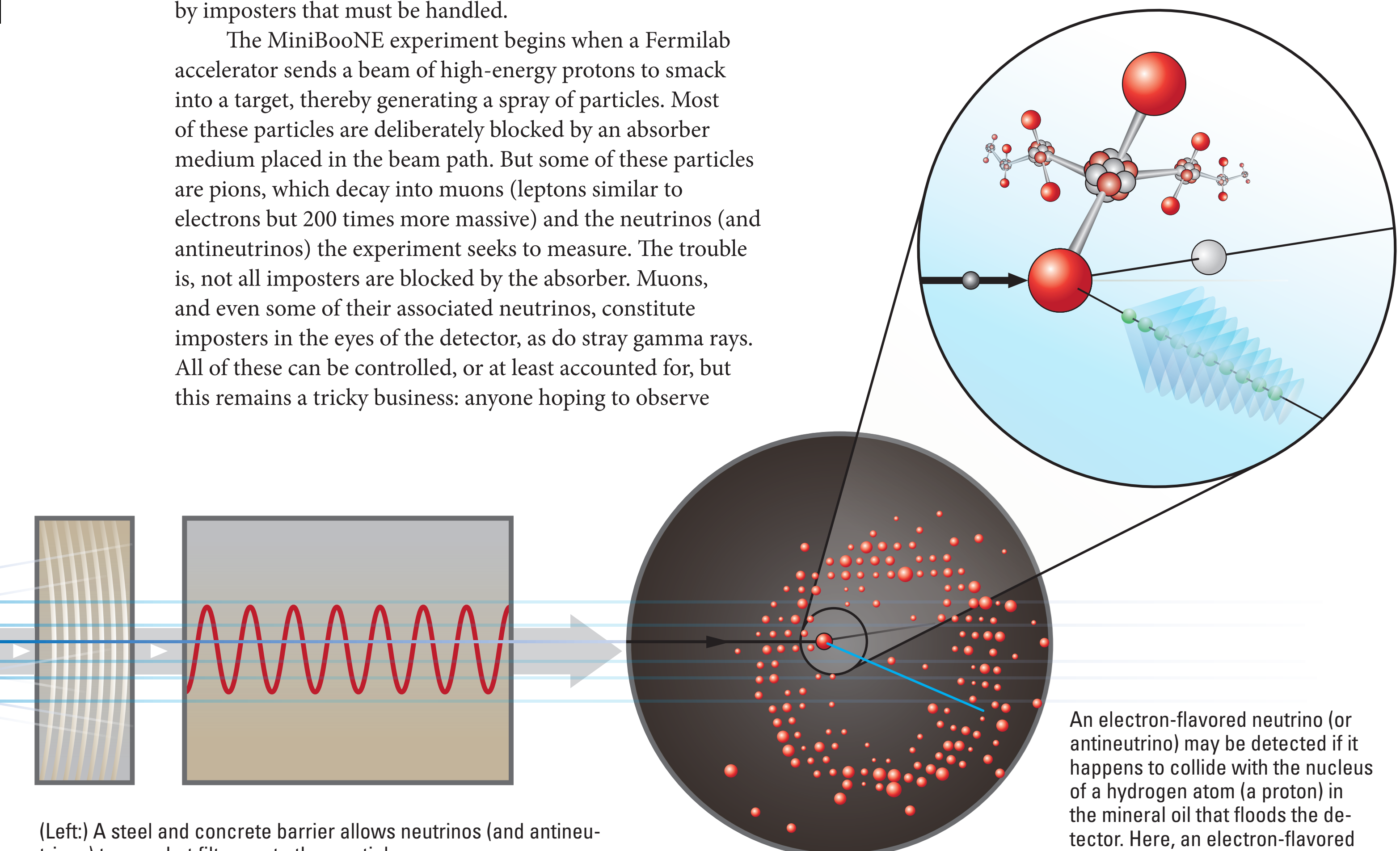
Pions enter a 50-meter-long air-filled pipe where they decay primarily into muons (or antimuons, depending on the charge of the pion) and muon-flavored neutrinos (or antineutrinos).

neutrino-induced electron or positron bleeds energy into the surrounding oil, causing another glow called scintillation, which spreads out spherically in all directions. “So you’ve got the Cherenkov cone and the scintillation glow together: that’s your neutrino signature,” says Louis. If either of these components is missing, the event is disregarded.

But despite this multiple-component recipe for detection, rejecting all the imposters remains a challenge. MiniBooNE employs a variety of methods to ensure that its detections are genuine. It lies underground beneath 10 feet of earth and has a special “veto shield” in order to prevent false signals that could originate with cosmic rays raining down from space. Even the neutrino beam that is deliberately aimed at the MiniBooNE tank is unavoidably accompanied by imposters that must be handled.

The MiniBooNE experiment begins when a Fermilab accelerator sends a beam of high-energy protons to smack into a target, thereby generating a spray of particles. Most of these particles are deliberately blocked by an absorber medium placed in the beam path. But some of these particles are pions, which decay into muons (leptons similar to electrons but 200 times more massive) and the neutrinos (and antineutrinos) the experiment seeks to measure. The trouble is, not all imposters are blocked by the absorber. Muons, and even some of their associated neutrinos, constitute imposters in the eyes of the detector, as do stray gamma rays. All of these can be controlled, or at least accounted for, but this remains a tricky business: anyone hoping to observe new physics must be prepared to observe new imposter physics instead. Thus, if the experiment’s results turn out as expected—perhaps matching the majority of neutrino experimental results and leaving LSND as the sole outlier—then the experimenters might feel satisfied they eliminated all the imposters. But if the results differ from expectations, how can experimenters ever be certain they eliminated them all?

One way to help expose the imposters is to alter the experiment, so that the signal from the neutrinos in the beam is the same but the signature from the imposters changes. “In order to make MiniBooNE sensitive to the same effects we saw at LSND, we had to design MiniBooNE to similar specifications, but we didn’t want to make an exact copy of



DATA SOURCE: FERMILAB

(Left:) A steel and concrete barrier allows neutrinos (and antineutrinos) to pass but filters out other particles.
(Right) As muon-flavored neutrinos (or antineutrinos) travel from the beam source to the MiniBooNE detector through 480 meters of earth, the flavor states “oscillate” as a probability wave: the probability of measuring the neutrino in each flavor state goes up and down. The wave shown is simplified for two-state mixing; three (or more) flavors would generate a more complicated oscillation pattern. For the wave shown, the troughs represent a 0 percent chance of transition (still muon flavor) and the peaks represent 100 percent chance of transition (to electron flavor). A point at the wave’s midpoint between peak and trough represents a 50-50 chance between the muon and electron flavor states.

An electron-flavored neutrino (or antineutrino) may be detected if it happens to collide with the nucleus of a hydrogen atom (a proton) in the mineral oil that floods the detector. Here, an electron-flavored antineutrino (black) collides with a proton (red), causing the production of a neutron (white) and a positron (green). The collision imparts enough energy onto the positron to create the light-equivalent of a sonic boom, sending a cone of visible light forward until it is picked up by the detector’s photomultiplier tubes.

LSND because what would we learn from that?" says Richard Van de Water, a MiniBooNE colleague of Louis's at Los Alamos. "If you do the math, you find that it's the ratio of the neutrinos' travel distance to their detected energy that is the critical factor. So with MiniBooNE, we changed the distance and the energy from LSND, but we kept their ratio the same." Indeed, the neutrino signal MiniBooNE attempts to isolate has a different dependence on distance and energy than that of its most troubling imposters.

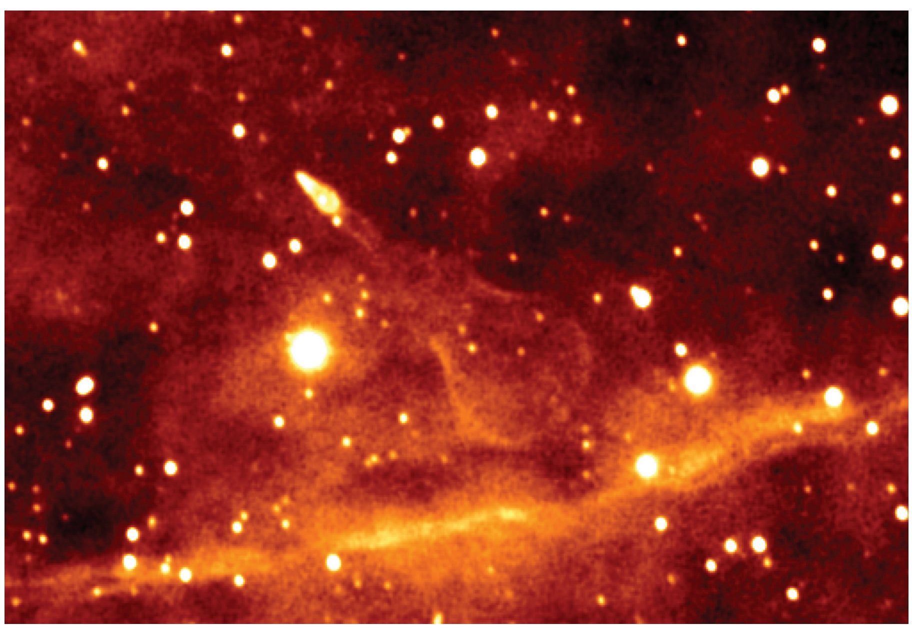
Flavor Physics

Quarks and leptons, including neutrinos, come in different varieties known as flavors (sometimes called families or generations) which determine how they behave in interactions involving the weak nuclear force. For example, when the pions in the MiniBooNE beam decay into muons and neutrinos—a process governed by the weak force—the neutrinos are always muon-flavored neutrinos (or muon-flavored antineutrinos, depending on the positive or negative charge of the pion). The reason this is so under the standard model is that weak flavors are always conserved in reactions and decays. So when a flavorless pion decays into a muon, it must also produce a muon-flavored antineutrino. Since we started with no net flavor, the decay must produce none: the flavors of a muon and a muon-flavored *anti*neutrino cancel each other out.

However, such weak flavor states are not defined in a simple way, nor are they necessarily permanent. An electron-flavored neutrino, for example, exists in a blend of multiple mass states—states with different masses—meaning that its mass is not precisely defined. Over time, the mass states interfere with one another in such a way that the flavor state fluctuates as well. Thus, an electron-flavored neutrino can change to muon flavor, and to a third flavor called tau, and back again repeatedly. Indeed, until the beginning of the twenty-first century, this very phenomenon stymied researchers trying to observe the neutrinos emitted by the Sun. Their detectors were only sensitive to electron-flavored neutrinos because those are what the Sun produces, but the neutrinos spontaneously changed to the muon and tau flavors during their journey here and thereby evaded detection. Such flavor changes are known as neutrino oscillations, the phenomenon LSND and MiniBooNE were designed to study.

Similar flavor oscillations had already been observed in the decay of some quark-based particles and had been theorized for neutrinos. In 2001, Canada's Sudbury Neutrino Observatory (where Los Alamos's Van de Water was detector manager at the time) was able to observe muon- and tau-flavored neutrinos from the Sun, thus explaining the observed deficit of (electron-flavored) solar neutrinos. With that problem solved, it seemed that the only thing left for neutrino physicists to do was perform experiments to nail down the exact parameters for neutrino oscillations—how different are the masses of the mass states? how far must a neutrino travel before it oscillates? and how does that distance depend on the neutrino's surroundings? Louis and others working on LSND, however, discovered there was much more to be done.

The LSND experiment happened to employ a beam of antineutrinos rather than neutrinos. Most of the physics community assumed that this choice made no difference; an



The Guitar Nebula was created when a massive star underwent a supernova explosion. The explosion left behind a neutron star, moving rapidly up and to the left in this image, elongating the surrounding material into a guitar-shaped cloud in its wake. Such powerfully-kicked neutron stars are common after supernovae, but it is unclear what causes the kick. One popular explanation involves a recoil from an asymmetrical release of sterile neutrinos. This particular neutron star is moving so quickly that it will eventually escape from the gravity of our Galaxy.
CREDIT: PALOMAR OBSERVATORY AND SPACE TELESCOPE SCIENCE INSTITUTE (HUBBLE SPACE TELESCOPE)

Left to right, Los Alamos physicists Richard Van de Water, Bill Louis, and Geoff Mills bravely stand up to the hundred trillion neutrino particles the Sun sends through their bodies (and yours) every second.

electron-flavored antineutrino would oscillate into a muon-flavored antineutrino just as a regular electron-flavored neutrino would. But when the LSND team measured the parameters associated with their antineutrino oscillations, they got wildly different results than other experiments had obtained for neutrino oscillations. "Since all the other experiments were consistent with each other—neutrinos from the Sun, from cosmic rays, from nuclear reactors, and from beams—a lot of people thought LSND was somehow mistaken," remembers Louis. Today, however, MiniBooNE appears to be confirming the LSND results: antineutrinos do not oscillate the same way as neutrinos do. That statement by itself is virtually revolutionary in the world of particle physics, but the novelty of the MiniBooNE results, and the LSND results they corroborate, runs much deeper.

Oscillating Interpretations

The equations governing neutrino oscillations depend on the mass states involved in a curious way. If we assume for simplicity that only two states are involved in the oscillation, then those two masses don't show up in the math explicitly; rather, it is the difference between the squares of the masses, Δm^2, that appears in the relevant equations. Data from solar neutrinos, oscillating from electron to the muon and tau flavors, peg Δm^2 for the associated mass states to about 0.00008 squared electronvolts, or eV^2 (mass quoted in units of energy as justified by Einstein's equivalency $E=mc^2$). And data from neutrinos spawned by cosmic ray interactions in the atmosphere, oscillating from muon to tau flavor, reveal Δm^2 for that oscillation to be about 0.002 eV^2. But LSND's oscillation data, from muon to electron flavor, is best fit with a much larger Δm^2 of around 1 eV^2.

If that 1-eV^2 measurement is correct, then it begs the following question: If there are only three flavors—electron, muon, and tau—then how can the difference between any two of the masses, squared or otherwise, be greater than the total of the other two? To see this, consider an example: If the squared masses were 2, 5, and 9 in some units, then the differences between pairings would be $5 - 2 = 3$, $9 - 5 = 4$, and $9 - 2 = 7$. The largest of these differences, 7, equals the other two added together $(3 + 4)$, as it must. So even if all three states were involved in the LSND oscillations, how could the 1-eV^2 measurement, which is far greater than the 0.002- and 0.00008-eV^2 measurements for the other two flavor changes, be correct? This question has perplexed neutrino physicists since 1995. And the fact that LSND used antineutrinos rather than neutrinos does not resolve the issue, since antineutrino masses, and antiparticle masses in general, never differ from the corresponding particle masses when measured in other, non-oscillation phenomena.

MiniBooNE was designed to either confirm or refute LSND's too-large Δm^2. As it turns out, it did both. First, using a beam of neutrinos (not antineutrinos), MiniBooNE found no oscillation from muon to electron flavor in the energy range of interest. This lack of oscillation agrees with the Δm^2 measured for solar neutrinos, which only oscillate after much greater travel distances. That result was reported in 2007, but by 2010, after switching to a beam of antineutrinos, MiniBooNE obtained essentially the same result as LSND, with Δm^2 between 0.1 to 1.0 eV^2 (this range will tighten over time as more data is collected). This is still too large to be explained with only the three known flavors since it exceeds the sum of the other mass-square differences.

So what about proposing the existence of a fourth flavor? That would be bold. Since all the other quarks and leptons exist in only three known flavors, adding a new flavor, like declaring an observed asymmetry between neutrinos and antineutrinos, is not exactly a minor tweak to the standard model of particle physics. But the MiniBooNE results, taken

Most of the mass in this cluster of galaxies takes the form of dark matter, which is difficult to observe because it undergoes no electromagnetic or strong nuclear interactions. Weakly-interacting neutrinos could act like dark matter, but the known types of neutrino are too light to be responsible for the gravitational fields of galaxies and galaxy clusters. Sterile neutrinos, however, could be massive enough to account for the universe's dark matter. In this image, gravity is warping the appearance of background galaxies and causing them to appear like distorted arcs. The blue-purple region indicates where most of the dark matter is located in order to produce this effect.

CREDIT: NASA, ESA, E. JULLO (JPL), P. NATARAJAN (YALE), & J. P. KNEIB (LAM, CNRS)
ACKNOWLEDGMENT: H. FORD AND N. BENITEZ (JHU), & T. BROADHURST (TEL AVIV)

in context with data from other particle colliders, are even more revolutionary than that.

Geoff Mills is a Los Alamos scientist working on the MiniBooNE collaboration with Louis and Van de Water. Prior to coming to Los Alamos, Mills researched properties of the weak nuclear force at the European CERN collider laboratory. One of these experiments measured how long the Z^0 particle—a particle involved in communicating the weak force—could exist before it underwent radioactive decay. Because that particle lifetime depends on how many different sets of particles it can decay into, including neutrinos and antineutrinos, the CERN measurement revealed how many flavors of neutrinos exist. The result was exactly three: electron, muon, and tau.

The CERN experiment pertained to decays mediated by the weak force. Therefore it would be more accurate to say there can be only three "active" flavors of neutrino—ones that interact via the weak force. But taken together with the LSND and MiniBooNE results implying the need for more (and more massive) flavors to account for the large measured Δm^2, neutrino physicists have been led to an unexpected conclusion.

As Mills explains, "If our antineutrino oscillation experiments can only be explained with one or more additional flavors, and we already know they can't be active, then evidently we need inactive, or sterile, neutrinos." Thus MiniBooNE, confirming results from LSND, points to three major advances in particle physics. First, it suggests a matter-antimatter asymmetry that had never been observed with leptons before (and had been observed only exceedingly rarely with quarks). Second, it implies the existence of a fourth flavor of neutrino. And third, it provides evidence for a new entity: a sterile neutrino. In fact, in order to accommodate MiniBooNE's different neutrino and antineutrino oscillation data, many researchers, including the Los Alamos team, conclude there must be at least two sterile neutrino flavors.

Murmurs of Approval

For now, the evidence for sterile neutrinos remains incomplete. The trouble isn't just the possibility of imposter particles creating false signals in the MiniBooNE detector; as with any new physics, there's also the possibility that other new phenomena are distorting the scientific inferences. For example, sterile neutrinos might in fact exist, but they might be unstable and decay in a way that tricks the detector. Or perhaps there's a new type of force altogether, rather than a new type of neutrino. Time will tell, as MiniBooNE continues to run antineutrino experiments for at least another year to improve the statistical significance of the results. The Los Alamos team also hopes to rearrange the MiniBooNE system to change the distance between the beam source and the detector, because if the number of electron-flavored antineutrinos observed varies with distance, that would be strong evidence that the effect is genuinely the result of an antineutrino oscillation with a Δm^2 that requires one or more sterile flavors.

In the meantime, MiniBooNE and LSND are not alone. Among several experiments that observe neutrinos emerging from nuclear reactors in power plants, about 6 percent of the expected antineutrinos appear to be missing. This implies that they are oscillating into unseen flavors over relatively short distances, which should only happen with a large Δm^2. These results from nuclear reactor experiments are consistent with MiniBooNE and LSND.

What if the new evidence for sterile neutrinos holds up? There are no obvious technological advances expected to stem from this new science, even though it's always possible that someday there could be. The rarely-interacting nature of neutrinos (and the never-interacting nature of sterile neutrinos!) limits their practical value because machines need to be enormous to capture just a few of them. Even the 12-meter-diameter MiniBooNE detector catches only one out of every trillion active neutrinos that are incident upon it, thus requiring years before it accumulates enough detections for a statistically significant result. But the new neutrino physics would make a real difference in certain astrophysical settings, where neutrinos' gravitational and inertial effects could be observable.

For example, sufficiently massive, noninteracting neutrinos could account for the universe's dark matter—invisible matter whose gravitational influence in galaxies and clusters of galaxies dwarfs that of the observable "normal" matter. And in the supernova that marks the death of a massive star and happens to involve a huge outpouring of neutrinos, any deviation from a perfect spherical explosion could send an excess of neutrinos, including sterile neutrinos, in one direction. If massive enough, sterile neutrinos could generate a recoil that sends the remaining stellar core—usually a neutron star—hurtling through space at high speeds, which has indeed been observed. Additionally, early in the big bang, when the universe was only a tiny fraction of a second old, extreme temperature and density conditions would have made neutrino interactions much more common than they are now. New physics describing how those interactions proceed could improve our understanding of how our universe evolved. The asymmetry between neutrino and antineutrino oscillations, for instance, could shed light on how our universe managed to allow matter, but not antimatter, to endure.

Back on Earth, Louis reminisces about the two decades he has spent investigating neutrino and antineutrino oscillations at Los Alamos National Laboratory. "If the evidence for sterile neutrinos holds up, I will count myself fortunate to have been involved in the discovery of such exotic physics." He pauses, then adds, "You know, even if it's not a sterile neutrino, we still know we've found something new which will be worth the effort to understand." ❖ LDRD

—Craig Tyler

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Squeezing Power from Pond Scum

The merits of renewable fuels abound, but so do limiting factors. We can already produce biofuels to run our cars, but if it costs $10 per gallon and requires petroleum products for production, why bother? We must see green—economic and environmental—if we seek to reduce our dependence on fossil fuels.

The United States currently imports at least half of its petroleum, 60 percent of which is used for transportation fuels, and resources are dwindling. With the world's population now surpassing seven billion people, the nation seeks a competitive alternative to crude oil.

Biofuel is a popular venture today, and hundreds of companies in the United States are now pursuing algae as a source of fuel and other economically valuable products. The discovery that many species of algae can produce large amounts of combustible fats and oils dates back more than sixty years, and algal biofuels research gained traction during the energy price surges of the 1970s. But then researchers turned their attention to conversion of agricultural products such as corn and cellulosic material (stalks and fibrous plants) into ethanol. Unfortunately, this approach is not without its downsides, as demand for farm-grown fuels would cause crop prices to rise, potentially threatening to leave mouths empty. Additionally, it suffers from other common problems of big agriculture, including the clearing of rainforests and the deadening of marine zones due to fertilizer runoff. And so far, crop-based ethanol has proven to be a low-performance fuel compared to petroleum.

Recently, algae have garnered renewed interest. Because algal biofuel must compete with petroleum in price as well as performance, it's fortunate that not only is algae a good source for fuel, but some of its byproducts are far more valuable per gallon than crude oil. But it still costs more than petroleum to produce, so algae's economy-energy-environment equation must be carefully balanced.

Algal Fuel for the Fire

Algae are aquatic microorganisms that use carbon dioxide (CO_2), water, and energy from light to make sugars, oxygen, and combustible fuel sources including lipids (fatty, energy-rich molecules) and hydrocarbons. The unicellular variety most biofuel researchers focus on, microalgae, is found in freshwater and marine systems. Some microalgae species can double their mass in one day and may contain up to fifty percent of their body weight as lipids.

Algae are valuable sources for fertilizer, proteins, essential fatty acids for nutritional supplements and pharmaceuticals, animal feed, and industrial products such as polymers in biodegradable plastics and rubber. Algal biomass can produce more burnable fuel on less land than traditional bioenergy crops—at least 32 times more oil than corn per acre annually—and its use in fuel does not compete with the world's food demands. It can be cultivated on nonarable land that is also undesirable for urban development and can be grown in nonpotable water containing salt, industrial waste, or sewage.

A photobioreactor (PBR) is a device that can contain and grow algae without the need for sunlight or sugars (required by ponds or fermenters, respectively). Los Alamos chemical engineer Munehiro Teshima designed and built this unique PBR to achieve exquisite control over gas flows and other factors such as temperature, illumination, alkalinity, agitation, and cell density. The reactor uses sophisticated sampling robots to take measurements and make adjustments in order to maintain ideal growth conditions.

Algae also have another advantage over other biofuels. Algal products produce enough energy to be used in high-energy density liquid fuels for aviation and long-haul trucks, something that cannot be said for corn-based ethanol, which only provides about half the energy per volume of jet fuel. In fact, algal-powered commercial planes took flight last year.

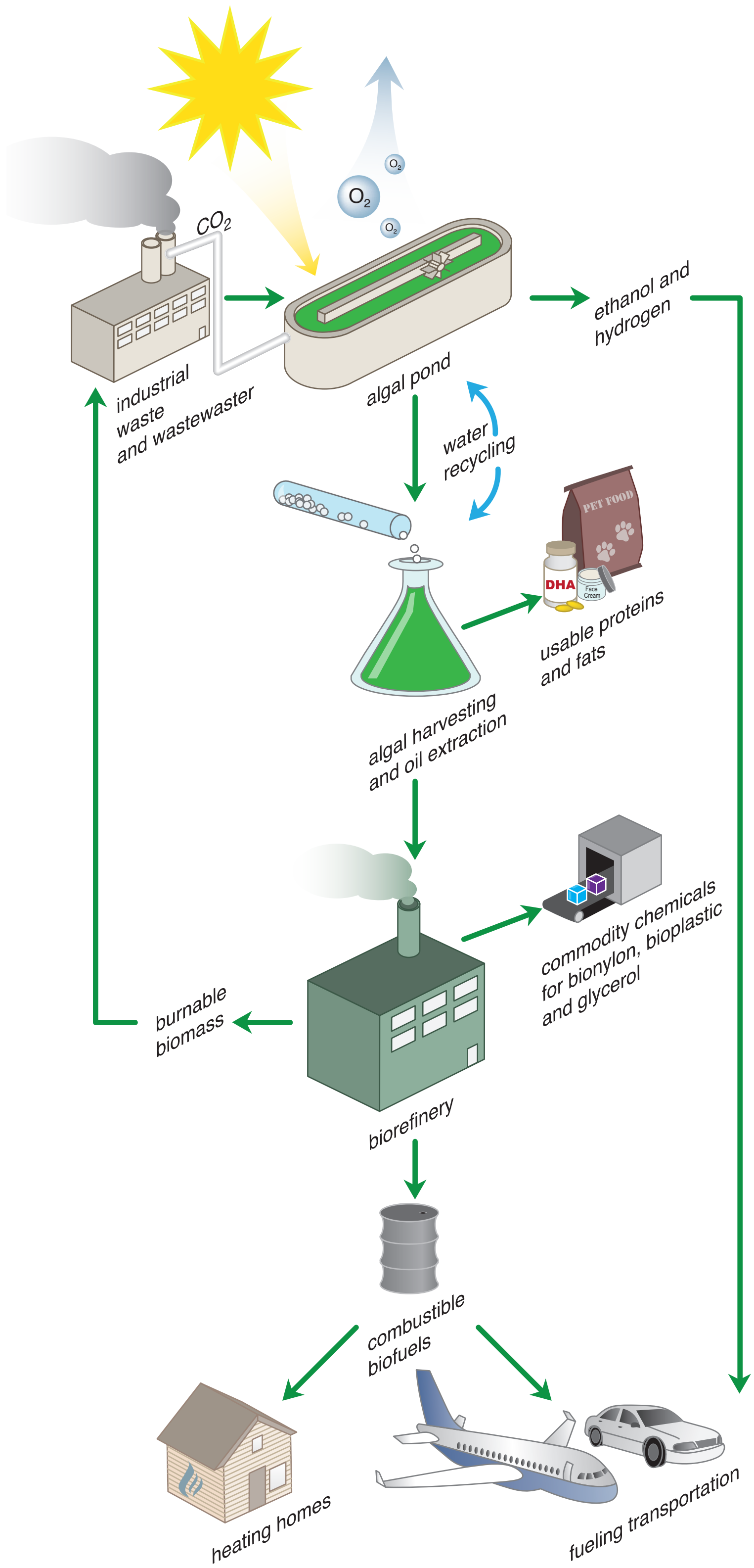
Biofuel production from algae, on the other hand, sounds simple and ideal: Add algae to wastewater tanks located in sunny locations with no commercial or agricultural value, and let the plant grow independently. Overfeed the algae to make them produce more fat (just like humans). And since algae require carbon dioxide for growth, they absorb dangerous greenhouse gases from the environment while simultaneously producing lots of valuable oil—a boon for our planet and our economy. It certainly sounds like a compelling plan. In reality, however, it's not so easy.

The production of biofuels from algae faces significant challenges. Large-scale algae-to-fuel production utilizing today's technologies is estimated to supply fuel that costs at least $8 per gallon (compared to about $4 per gallon for soybean oil). So production efficiency and output of valuable byproducts must be increased for algal biofuels to be a viable option. The organism must be improved for it to thrive on a diet, to survive in less-than-ideal environments, to surrender its fats without a fight, and to provide sufficient power when consumers put the pedal to the metal.

The Perfect Strain

Countless species of microalgae exist, and scientists are looking for ideal algal strains that grow rapidly and accumulate large amounts of oil with minimal inputs that survive despite a large variation in temperature and water quality. Their target is to maximize production of both hydrocarbons and lipids through understanding and improving the biosynthetic pathways involved.

Renowned crop researcher and molecular biologist Richard Sayre recently brought a large team to Los Alamos to address algal problems. Sayre is currently working on multiple methods to increase algal performance. With one method, Sayre genetically engineers algae to absorb light



Scientists are improving methods to make the algae-to-fuel process more economical and environmentally friendly. This illustration reveals how algae can thrive in wastewater, remove carbon dioxide from the atmosphere, and surrender their entire biomass to be used. Algae's products are diverse—biogasoline, cosmetics, plastics, and food supplements, to name a few—and Los Alamos researchers have already made growth, harvest, and production methods more efficient.

more efficiently to increase production and decrease resource use. The Lab is a partner in two biofuels consortia—the National Alliance for Advanced Biofuels and Bioproducts (NAABB) and the National Advanced Biofuels Consortium—to develop "green" biofuels. Sayre is the chief scientist for NAABB, which is directed by his Los Alamos colleague José Olivares.

Algae evolved to grow in low light, so their photosynthetic antennae only use about one quarter of the energy they absorb from the sun. But even though they don't use all the solar energy, they hog it and prevent algae located deeper in the water from seeing any sunlight. Sayre created mutants with much smaller antennae designed to absorb only as much light as they need, thereby allowing other algae to soak up more light. This improvement allows biofuel producers to use deeper ponds with layers of algae, which decreases the amount of both land and water needed for cultivation. Thus, a given pond can produce more algal biofuel.

The Laboratory's Genome Science Group is sequencing and assembling five algal genomes, with three more in the near future. The group examined several algal gene sequences to determine what genes are important for lipid production. Because most algal production systems are open ponds, it's important to understand the entire pond community in order to maintain stable cultures. Therefore, the team is sequencing DNA from the mixed environmental samples.

Los Alamos biochemist David Fox and his team are pursuing algal compounds that produce hydrocarbons having a structure similar to gasoline—flammable liquid hydrocarbons. These hydrocarbons can simply be dropped into an existing oil refinery's infrastructure and "cracked" to provide auto fuel similar to gasoline. Fox's team is collaborating with researchers at Texas A&M University to identify the optimal process for conversion of CO_2 and light to hydrocarbons by using genetic engineering to manipulate the network of metabolic processes performed by algae.

Other teams at Los Alamos are working on different angles. One led by Pat Unkefer, for example, increases the photosynthesis rates by raising the amount of carbon dioxide the organism takes from its environment and converts to carbohydrates, while also increasing the efficient use of nitrogen.

The Sweet Spot

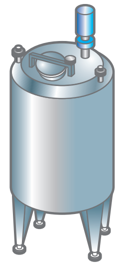
Scientists know how to speed up algal reproduction, but can they simultaneously accumulate lipids at a matching rate? To be cost competitive, algal biofuels production must be swift, but when the organism diverts all its energy towards proliferation, it consumes its fat reserves. An optimal combination of nutrients, light, and temperature must be created that balances high growth rates and lipid yields.

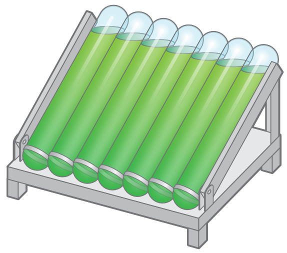
"People underappreciate how difficult it is to improve upon nature," says Fox. "Gene function discovery is difficult, but bioengineering algae for much improved production of biofuels may border on an intractable problem. We want a fast growing organism that also has a high energy density. It's a major barrier to overcome."

Los Alamos bioscientist Cliff Unkefer monitors algae's growth. Unkefer and his colleague Pete Silks recently demonstrated a high-yielding chemical process to convert triglycerides obtained from algal lipids into high-energy hydrocarbon biofuels for aviation. The process removes oxygen atoms from the algal triglycerides and reforms the resulting high-molecular-weight hydrocarbons into lower-molecular-weight hydrocarbons that can vaporize and ignite quickly.

Fermentation Tank

Easy to maintain, prevents contamination, and achieves high biomass concentrations with less water but requires sugar as an energy source.



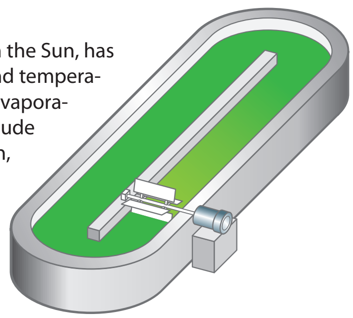


Closed Photobioreactor

Easy to maintain, and high surface-to-volume ratio supports high cell densities. Requires cleaning, light exposure, and energy-intensive cooling. Suffers from mixing and gas-exchange inefficiencies.

Open Pond

Uses free energy from the Sun, has lower capital costs, and temperature is controlled by evaporative cooling. Risks include culture contamination, loss to predators, and weather fluctuations. Requires abundant land and water.



Sayre agrees and thinks improved results may materialize by blending different algal growth strategies. Some species of algae can grow autotrophically—outdoors using sunlight as the energy source—but the process is slow. Some species can be grown heterotrophically—fed glucose or fructose inside a fermenter (sugar instead of sunlight)—but this is expensive, produces substantial CO_2 as a byproduct, and risks contamination since bacteria thrive in the presence of sugar. Some species are mixotrophic, deriving energy from both sunlight and sugar. Sayre believes a hybrid model where the algae are grown outside with captured CO_2 and wastewater is sustainable. No oil is produced until the next phase, when the mass is briefly fermented inside a tank with small amounts of sugar. There, the lipid content is increased from miniscule amounts to 70 percent with a 24-hour turnaround, according to Sayre.

Quenching a Mighty Thirst

Algae has a major advantage over traditional agriculture in that it can thrive in contaminated water, but it still requires a substantial amount of water. Experts predict mass cultivation of algae will require at least 350 gallons of water per gallon of oil produced. Water consumption needs to be reduced if algal biofuels are going to be economical and environmentally friendly.

Pilot plants are trying to use wastewater or water from a saline aquifer. According to Sayre, the saline water model is not ideal because the water evaporates, leaving behind salts or toxins that require expensive mitigation to prevent environmental contamination. However, it may be possible to drain briny water to evaporation ponds in order to recover the salts for use by the chemical industry.

Municipal wastewater as a growth medium may present a win-win situation for algal producers and communities because the algae remove contaminants and utilize nutrients that otherwise pollute the water, such as raw sewage or fertilizer runoff. Algal use of wastewater—rich in carbon, nitrogen, and phosphorous nutrients—could reduce the expense and the environmental cost of producing fertilizers, while removing environmentally damaging chemicals from the water. The residue could then be used as fertilizer.

Produced water, a byproduct pumped to the surface during fossil-fuel extraction that contains bicarbonate and other nutrients, is also becoming an attractive growth medium for algal biofuels, although it may require pretreatment to remove certain toxins. Currently, oil and gas production brings about 800 billion gallons of brackish produced water to the surface. Los Alamos scientist Enid Sullivan and colleagues at Eldorado Biofuels (a New Mexico company) recently joined industry and NAABB consortium partners to conduct the first pilot-scale test of algae growth using water from an oil-production well in New Mexico. The researchers grew salt-tolerant, oil-producing algae in 80-gallon reservoirs of city water with varying amounts of produced water mixed in. When the concentration of produced water was at low levels, algal growth was comparable to that in the control group containing unadulterated city water. Growth became limited as more produced water was added, and researchers are now testing bicarbonate and salinity levels to find the ideal mix.

Land, climate, and algal growth are interlinked, and not all regions in the country provide enough sun, water, and carbon dioxide for growing algae. Roughly 800–2600 acres are needed to produce 10 million gallons of algal oil, according to the Department of Energy. A 2010 study by Pacific Northwest National Laboratory (PNNL) reports ponds should not be placed in urban areas or on conservation and agricultural land if algal biofuels are to be profitable. Sunny regions with average temperatures above 55° are ideal, and analysis revealed the Gulf Coast states

Los Alamos researchers Richard Sayre (left) and José Olivares founded a new international journal, *Algal Research,* launching early this year. These Los Alamos scientists also organized the first International Conference on Algal Biomass, Biofuels and Bioproducts last year.

and portions of the Southwest are optimal. PNNL's study reveals that algal biofuels produced from 21 billion gallons of American algal oil could replace 17 percent of the United States' imported transportation fuels, and it could be grown on parcels of land that, taken together, are roughly the size of South Carolina.

"Production rates from algae are at least tenfold greater than regular agriculture," says Cliff Unkefer. "And it doesn't need to be grown in rich river-bottom land. If we can get productivity high enough we could lower the land requirement by a factor of ten compared to agricultural crops such as corn."

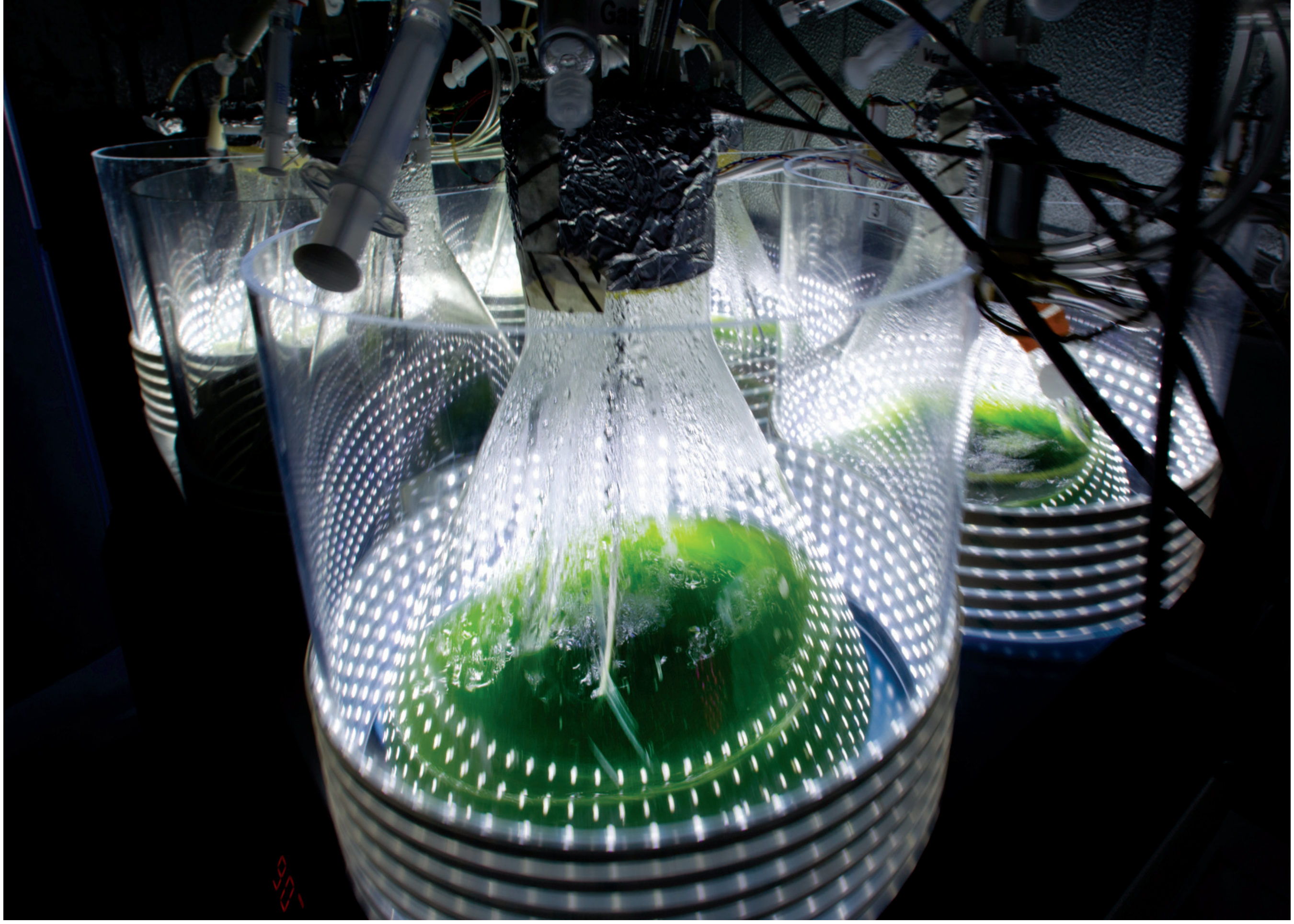
Algal Bloom

Nitrogen is essential for the growth of algae's DNA, RNA, and protein—building blocks of life. Earth's atmosphere is composed of 80 percent nitrogen, but not in a form plants can use, due to the nitrogen molecule's strong triple bonds. Therefore nitrogen and other mineral nutrients must be supplied to crops via fertilizers, the production of which is extremely energy intensive. Fertilizers are usually synthesized using atmospheric nitrogen and natural gas, a fossil fuel. Agriculture loses 75 percent of the fertilizer input to soil seepage, which is harmful to the environment. Fortunately, algal ponds are protected from this leaching into the ground, but the fertilizer is still expensive.

The ammonia (NH_3) used to produce fertilizers is commonly synthesized using a process that requires high temperatures and very high pressures. As a result, 3–5 percent of the natural gas produced in the world is consumed in the process. Los Alamos chemist John Gordon and his colleagues are attempting to develop low-cost, low-energy (ambient temperature and pressure) synthetic approaches to generate NH_3 using abundant metals such as iron.

An alternative to making fertilizers cheaper is to develop a way to use less of them. Stressing algae by removing or decreasing the availability of a key nutrient, including those found in common fertilizers, can result in high lipid production. Therefore, Pat Unkefer and her team are working on understanding this metabolic mechanism and exploiting it to generate high productivity. However, just removing the nutrients does not mean that the algae will become fat. In fact, they are more likely to die if the nutritional manipulations are not carefully executed. When algae are stressed from lack of nutrients (or other factors such as drought or temperature fluctuations), they absorb more sunlight in their chloroplasts than they can use during photosynthesis and CO_2 fixation, and molecular oxygen is activated. The plants experience photo-oxidative damage, which can lead to cell death. However, as long as the plants are not overstressed, they produce lipids as well as gummy residues called isoprenoids (another biofuel source) to protect themselves by storing light energy as chemical energy.

Los Alamos scientists are researching algal growth in open-air ponds in New Mexico and Texas. Open ponds that do not require much mechanical mixing (to incorporate nutrients) need 20–100 days for algal growth. High rate ponds like this one, which mix the solution with paddle wheels, allow cultivation in 4–10 days, but they are more expensive to run. CREDIT: NEW MEXICO STATE UNIVERSITY



A closed photobioreactor system is essentially a series of plastic or glass containers for water and algae. Proponents of such bioreactors (compared to open ponds) say the growth environment can be more easily controlled; they prevent evaporation; and light penetrates through all sides of the container, which increases cell density. However, bioreactors suffer high materials and energy costs as well as mixing and gas-exchange inefficiencies; therefore scalability remains problematic.

Capturing Carbon Dioxide

Algae consume CO_2 during photosynthesis. They can get this CO_2 from the atmosphere, but the uptake rate is limited by its slow diffusion through the surface resistance of the water in the cultivation system. Accelerating algae's growth rate requires boosting both the CO_2 supply and its uptake speed.

To address the supply problem, Los Alamos researchers have designed and constructed a system for extracting CO_2 from the exhaust streams of power plants and concentrating it for algal consumption. This method kills two birds with one stone, since the exhaust CO_2 is an unwanted greenhouse gas emission anyway. Researchers are determining what algal species can survive the exhaust gases' blistering temperatures and optimizing the delivery system.

Two teams at the Laboratory (led by Sayre and Zoë Fisher) are boosting algae's metabolism by a genetic modification that uses an efficient human enzyme responsible for CO_2 regulation in red blood cells to increase algal growth. The enzyme catalyzes the inter-conversion of CO_2 and bicarbonate, which the algae readily take up. Fisher uses data from a joint neutron and x-ray study—the first of its kind—to better understand the enzyme properties and reaction rate. Sayre reports this genetic work increased algal photosynthesis rates 30–136 percent, depending on test conditions.

Making Pondscum Profitable

So once researchers have mastered plant growth, how do they squeeze the precious oil out? Harvesting the algae from its growth medium and then extracting the oil can be quite costly, accounting for almost 30 percent of the total cost of current algal biofuel production systems. But Los Alamos researchers discovered a way to use sound waves to harvest algae. The Ultrasonic Algal Biofuel Harvester uses ultrasonic waves to concentrate algae in a solution, rupture the algae to release the lipids, and then collect the lipids and other useful byproducts. The researchers, led by Babetta Marrone, are optimizing this technology into a portable device.

Conversion of algae to biofuels requires dewatering before extracting usable products. This can be daunting since the mass of water in a growth pond exceeds that of the algae by 999 to one. Recently, scientists Pulak Nath and Scott Twary, from the Los Alamos physics and bioscience divisions respectively, genetically engineered magnetic algae to investigate a novel harvesting method: pulling the algae from the water with a magnet. The team took a gene that is known to form magnetic nanoparticles in certain bacteria and expressed it in green algae. This project is in the early stages, and Nath is working to optimize it. Extraction—getting the oil out—is also being optimized. One option Twary is examining is to use rotating magnetic fields to heat up the algae, causing their cells to rupture and release lipids. The team is investigating how the metals in the magnetic nanoparticles could interfere with the algal chemistry or downstream byproducts (e.g., high levels of iron in biomass waste could be toxic to cattle therefore undesirable as an animal feed) and how to mitigate such potential problems. Once the algae is magnetically separated, some of it can be used for biofuels or commodity byproducts, and the magnetic nanoparticles can be recovered for use in biomedical imaging and cancer treatments.

Los Alamos student Calla Glavin (left) and Taraka Dale, a researcher in the Bioscience Division on the Ultrasonic Algal Biofuel Harvester team, measure the lipids harvested from algal cells.

Apart from the new magnetic approaches, oil extraction is usually done by one of two methods: mechanical or chemical. The mechanical method requires drying the algae, then pressing or crushing the oil out of the remaining biomass. It is energy intensive because of the dehydration process. The chemical method usually requires the use of toxic chemicals (such as benzene or hexane) as solvents, liquids that extract the oil from the plant. The oil is then distilled from the resulting solution. Los Alamos materials chemist Rico del Sesto and Fox developed a potentially new method for biofuel extraction using a benign class of solvents known as ionic liquids. Early results are promising, with the dual effects of extraction of hydrocarbons with minimal toxicity to the algae.

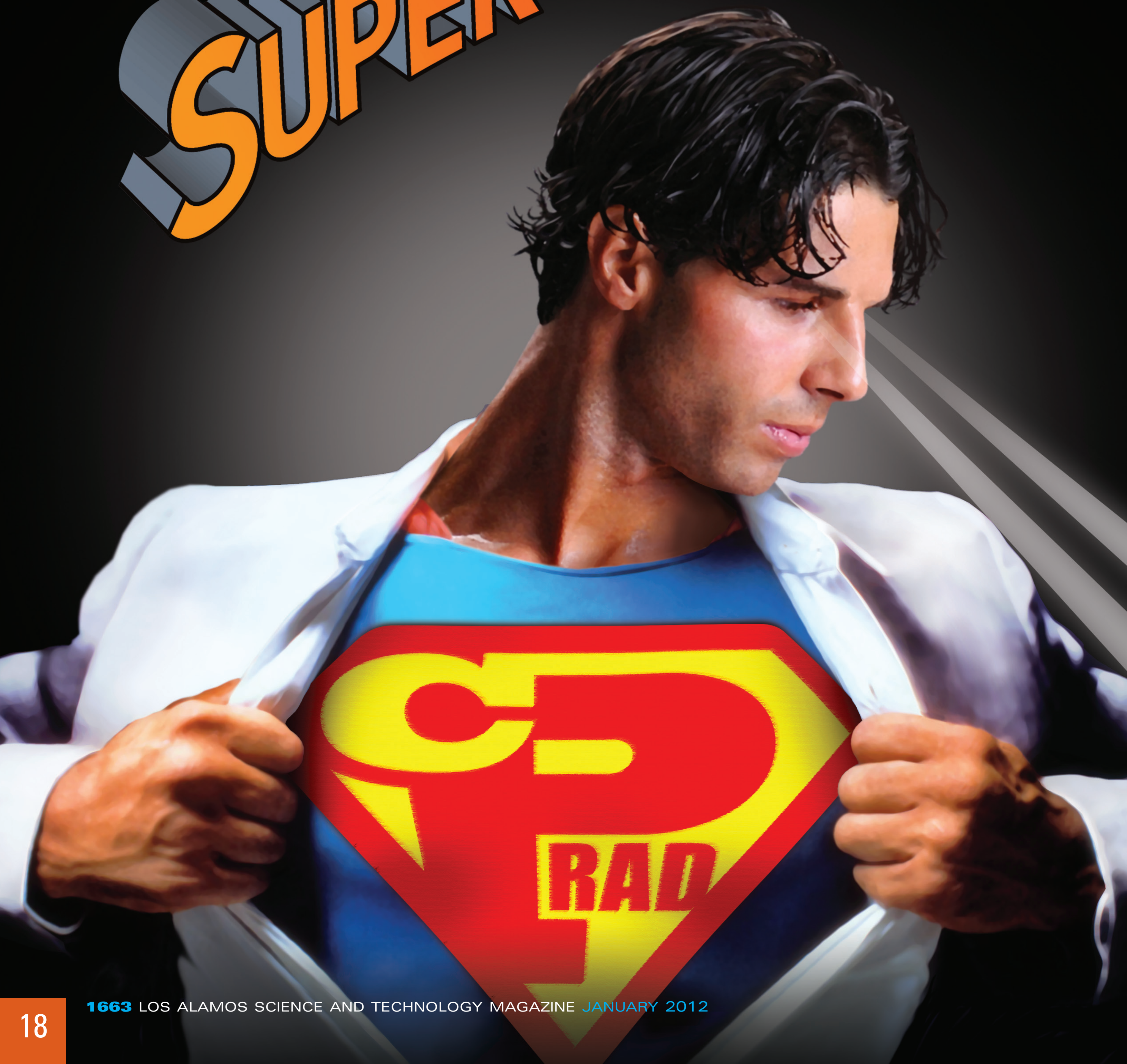
Each of these harvesting and extraction methods discovered at Los Alamos may help level the playing field against petroleum. But it's not easy being green. Energy links the environment, the economy, and our society together; all three are vulnerable to changes in the energy sector.

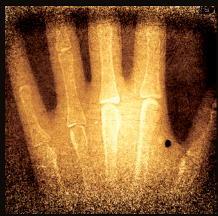
Since its inception, Los Alamos has been tasked to make pioneering discoveries to protect the nation, and today, energy security is an important component of that protection. In turn, algal fuels may become an important component of energy security if researchers can find ways to further cut biofuels' costs while increasing their production. Such progress would build upon the Laboratory's recent successes that helped rejuvenate decades of biofuels research and development. With promising leads on every aspect of biofuel production, Los Alamos has every reason to be optimistic. ❖ LDRD

—Kirsten Fox

Look! There at Los Alamos! It's an imager!
It's a diagnostic! It's...

SUPER CPRAD





Suppose for a minute that Superman had come to Earth endowed with proton vision, whereby he could emit beams of high-energy protons from his eyes and thus see through any substance, including dense materials like lead or plutonium that are opaque to his celebrated x-ray vision. He would also be able to follow with astonishing clarity and detail the nearly instantaneous changes an object goes through when subjected to extreme forces, such as when hit by explosion-driven shock waves. Accordingly, Superman's proton vision would have been a remarkable boon to the nuclear weapons community, which, since the days of the Manhattan Project, has wanted to peer inside a detonated nuclear weapon and watch its plutonium core implode and go critical.

Then suppose again that the Man of Steel could see the streams of cosmic-ray muons that continually race down from the upper atmosphere. Highly penetrating, the ghostly muons can whiz through a mountain of rock and dirt, but they scatter in characteristic ways from plutonium or uranium, even when those bomb-making materials are hidden behind layers of lead or otherwise concealed. If Superman were stationed at a border crossing, his "muon vision" would allow him to spot those telltale ripples in the muon stream and quickly intercept the illicit materials. It goes without saying that with proton or muon vision augmenting his powers, Superman would have been a lynchpin for nuclear stewardship and a champion in the war on terror.

Now admittedly, most people would consider the enhanced vision of a fictional superhero largely irrelevant to their lives. It's just that proton and muon vision are both as real as the Earth is round, and are already being used by scientists to confront the problems of a complex world. And that kind of vision is anything but irrelevant.

Charged-Particle Radiography

Protons and muons are charged particles that for years have been employed to make x-ray-like radiographs of an object's interior (a radiograph being a photograph made with non-visible light), as well as utilized to measure thicknesses, identify materials, and provide information about dynamic events. Indeed, muons were used as early as 1955 to measure the depth of a mineshaft within a mountain. Over the years, Los Alamos scientists helped drive the development of proton radiography (pRad) and muon tomography (μTom), and have recently demonstrated the capabilities of high-energy electrons in electron radiography (eRad). Collectively, pRad, μTom, and now eRad go by the catchphrase "charged-particle radiography," or cpRad.

While similar to each other in a block-diagram sense, each radiography has its pros, cons, and appropriate applications. Proton radiography can make movies of ultra-fast events, and is often used to probe components of nuclear weapons, obtaining information that can help keep our nuclear deterrent safe and reliable. Muon radiography is able to probe giant objects such as tractor trailers or shipping containers, and is close to being deployed at points of entry to guard against the smuggling of nuclear contraband. Researchers are even eyeing eRad as a tool that can help them develop the next generation of materials. So while not as awesome as a superhero, cpRad is still pretty super.

Above: A prosthetic hand (manufactured with an internal bone structure) illustrates the capability of charged-particle radiography. The false-colored image was obtained using high energy protons.

Super pRad

Proton radiography goes back at least 40 years, with an early pRad system described in a 1968 issue of *Science*. The key to making that early system work was understanding the relationship between a material's density and the distance a proton travels in the material before stopping.

A fast-moving proton passing through a substance loses energy to the electrons and nuclei of the substance's atoms—a little at first, but more and more as the proton slows down. If the material is thick enough, then similar to the way a spinning top teeters and abruptly falls, ending its spin, the energetic proton travels a certain range within the material, after which it quickly loses the bulk of its energy and abruptly stops moving (is absorbed). If a pulse of many billions of protons enters a material, all the protons will stop in relatively close proximity to one another, scattered about that range.

The early pRad system exploited this effect. The proton energy was chosen such that its range was about equal to the object's thickness. Then some of the protons were absorbed while the rest emerged from the object. The actual number that exited from a particular location depended sensitively on the amount of material encountered by each proton; that is, the transmission was proportional to the thickness of the object at that location.

The exiting protons would hit a piece of photographic film, exposing a small spot—the fewer protons that emerged,

	DARHT*	pRad	μTom	eRad
Probe	x-ray	proton	muon	electron
Source	accelerator	accelerator	cosmic ray	accelerator
Images	up to 5	about 32	1	many
Field of View	tens of cm	tens of cm	m	mm
Resolution	10–100 μm	10–100 μm	cm	100 μm

*Dual Axis Radiographic Hydrodynamic Test   m = meters, cm = centimeters, mm = millimeters, μm = micrometers

the less the exposure. In the black and white photo made from the developed film, blacker regions corresponded to the object's thicker, denser parts. Variations in thickness as small as 0.05 percent were discernable.

The pRad system housed at the Los Alamos Neutron Science Center (LANSCE) is as evolved from that early system as a camcorder is from a pinhole camera. The major advance is that instead of using the proton's range to map out the object's thickness, the angular spread of the emerging protons is used to map out the areal density; the latter is the amount of material encountered by the proton as it traverses the object. It's equivalent to the material's density times the length of the path taken by the proton (in units of grams per square centimeter).

The relationship between exit angle and areal density exists because a proton tends to scatter, or change its direction of travel, when it runs into atoms—their electrons, or their nuclei. Higher areal densities lead to more scattering and a broader angular distribution for the transmitted protons.

Once they exit, the protons begin to follow the magnetic field lines produced by several pairs of tractor-sized electromagnets. The carefully designed, high-efficiency magnetic "optics"—briefly discussed on the facing page—transport a proton from a point on the back of the object to a pixel on a multi-pixel detector. But scientists can also adjust the magnets to enhance the image contrast and resolution. Furthermore, they can insert a magnetic "magnifier" that, like a microscope objective, provides magnification at the expense of a reduced field-of-view.

The magnetic optics also creates images in two locations at once, so that the modern pRad system can do something that no other radiograph can manage—it can take a series of images of an object that is changing substantially faster than the blink of an eye.

"We do many dynamic experiments, which is a euphemism for saying we typically blow our test object up," says Andy Saunders, deputy group leader for the Subatomic Physics Group at Los Alamos. "We'll detonate a high-explosive and watch how the detonation wave advances through the material. We're able to capture the entire process with high resolution, routinely taking 30 or more images of the event."

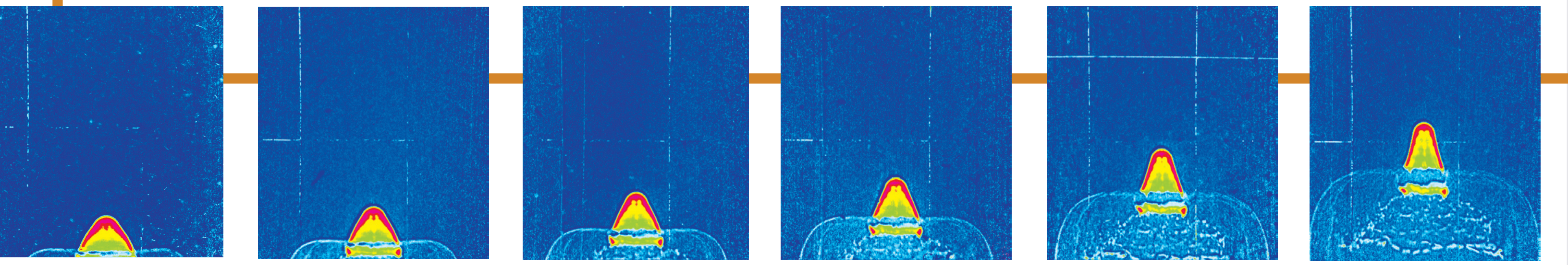
Remarkably, pRad technology was developed on a shoestring budget. Initially, a large fraction of the money came from Laboratory Directed Research and Development (LDRD) funds, but funding was dicey. "Let's just say that we never had any money problems, because we never had any money," jokes Chris Morris, one of the driving forces behind both pRad and μTom. "That was half the fun, figuring out what we didn't have the money to do, then figuring how to do it anyway."

It seems that sheer scientific tenacity was what kept pRad going—that and a strong sense of purpose, or perhaps a sense of irony. For while the technology grew out of basic research—developed by scientists whose bread and butter was measuring nuclear-reaction parameters—the motivation was weapons related. Given the proton energies available at LANSCE, pRad would be almost ideal for seeing how materials performed inside a detonated nuclear weapon.

Super Application

Top scientists still lack a complete understanding of the complex phenomena that occurs inside a nuclear weapon after it is detonated, when exquisitely timed explosions send the shock-wave equivalent of a tsunami racing towards a thin plutonium shell. Slammed everywhere at once, the shell is instantly driven inward at supersonic speeds (it implodes). Its density skyrockets, the number of fission reactions increases exponentially, and at some point, the total energy released by fission exerts enough pressure to blow the compressed

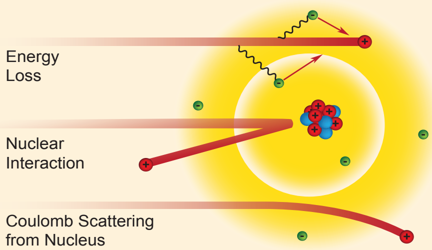
A copper projectile forms and takes flight in this series of pRad images. The newly designed projectile, intended to generate shock waves in a test object by impacting it at roughly 3 kilometers per second, forms after a small explosive charge is detonated beneath a thin copper dish. The dish deforms and the projectile moves out. The images verify that the projectile formed as expected, but they also highlight pRad's unique ability to take multiple frames of a rapid, dynamic event.



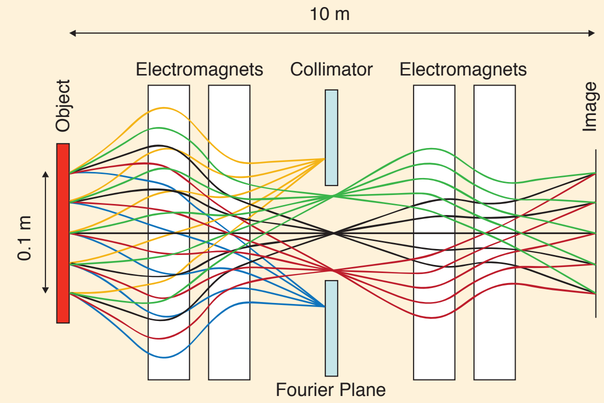
Contrast and Resolution

Proton radiography uses a beam of high-energy protons from a particle accelerator to take x-ray-like images of a target—typically a piece of material, but often an entire object. Before it hits the target, the beam is pulsed, collimated, and expanded in diameter by a set of electromagnets. Thus, a pulse of protons, all moving along parallel trajectories, uniformly illuminate the target.

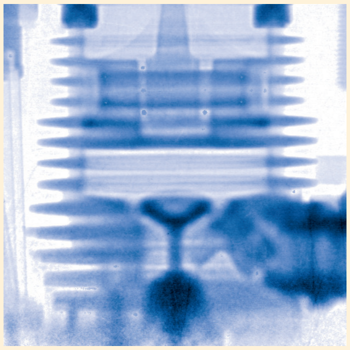
(Below) Penetrating the target, the speedy protons ionize atoms, so each proton continually loses a small amount of energy as it travels. With an initial energy of hundreds of million electronvolts or more, each proton will likely pass through the object with energy to spare. However, due to its interactions with the atomic nuclei, a proton will likely deviate from its initial trajectory. Collisions or near misses typically result in large directional changes, while longer-range interactions with the nuclear electric charge (Coulomb scattering) result in smaller changes. The net result is that protons passing through denser or thicker parts of the target tend to scatter more often, and so emerge from the target at larger angles from their initial trajectory.

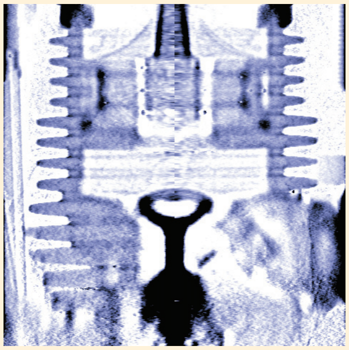


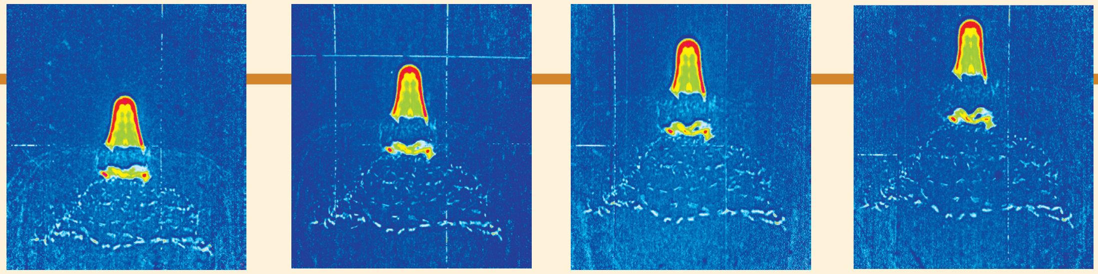
(Upper right) A series of electromagnets capture, transport, and focus each exiting proton onto a detector. The figure shows the paths of protons through the so-called identity lens. Five exit points are shown, each point having five potential exit trajectories. All protons that emerge from a point at the back of the target, regardless of exit angle, get focused to the same point in the image plane. But the exit angle correlates with an areal density—the density along the path taken by the proton through the target (grams per square centimeter). If all protons were allowed to propagate to the image plane, the result would be a loss of contrast because a spot in the image plane would represent a range of areal densities. Similarly, each exit trajectory represents a proton with a different momentum, and the magnets would focus each to a different image plane. The result would be a loss of resolution (each point in the image blurs into its neighbor). But remarkably, a set of magnetic lenses can be configured so that in an intermediate plane (Fourier plane), protons with large exit angles get focused to large diameters about the beam axis, and those exiting at smaller angles get focused farther away from the beam axis. An aperture can then remove the large-angle, slowest protons. Those that continue to propagate through the lens recombine at the image plane with narrower angular and momentum distributions, improving both the contrast and resolution of the image.



(Right, top) This false-color pRad image is of a model airplane engine. The different intensities correspond to different areal densities. The piston and piston rod are clearly visible, as are the cooling fins. The lower image has been processed so that contrast differences now represent differences in volume density.







(A) Because high-energy muons are created continually in the atmosphere, muon tomography can be set up anywhere. Back in the mid-1960s, it was used to look for hidden rooms within the Pyramid of Chephren in Egypt. (B) It can also be used to look for special nuclear materials hidden in everything from large shipping containers to small vehicles.

plutonium to smithereens (along with everything else in sight). It's all over in a tiny fraction of a second, and it all has to work perfectly.

Or maybe it just needs to work within a smidgeon of perfectly? How does one begin to answer that question, or begin to quantify "smidgeon"? One place to start is to understand all aspects of the implosion process, including how fluid instabilities and material defects impact the exponential growth of fissions.

The United States, however, ceased nuclear weapons tests nearly twenty years ago, making it virtually impossible to obtain new data under relevant conditions. So instead, the community has settled for testing individual components and materials under close-to-relevant conditions, then piecing together the results using various models. Then there are experiments to test the models, simulations to check the experiments, tests to verify the simulations, and occasionally a so-called hydrotest on a full-scale (non-nuclear) weapon surrogate to check everything.

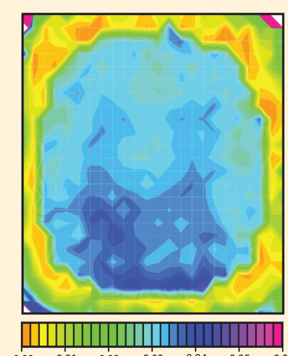
With the energy available from the linear accelerator at LANSCE, a proton will pass through a piece of lead on the order of 10 centimeters thick, corresponding to an areal density that is appropriate for the objects that weapons scientists want to study. So in terms of scale, pRad is a good match for problems of interest to the nuclear weapon's community. But about half of its Los Alamos workload is unclassified.

If there's one disadvantage to a pRad imaging system it's that with the over-sized magnetic lenses and the need for a source of energetic protons, the entire setup is forbiddingly complicated, sort of the way the Hubble Space Telescope differs from a pair of binoculars. At present, proton radiography resides at LANSCE, tethered to its proton accelerator. It's the only place in the country where proton radiography is performed.

Dial μ for Assistance

This past March, a 23-foot-high tsunami struck the Tohoku region of Japan and destroyed the Fukushima Daiichi nuclear power plant. It is still uncertain as to the status of the reactor core—the large, tower-like assembly of fuel rods that contains not only the uranium and plutonium fuel, but also the extremely radioactive waste products of nuclear fission. If the core remains intact and standing, it should be possible to remove the assembly as a unit, and execute some strategy to mitigate its hazards. But if the core melted and nuclear fuel spilled from the fuel rods, suffice it to say there are no easy solutions.

Los Alamos might be able to assess the status of the core by scaling up a demonstration muon tomography system so that it's capable of imaging the inside of the reactor. The uranium and small amount of plutonium in the fuel assembly is heavier and contains more protons per nucleus than any of the steel, concrete, or other materials making up the reactor; hence, the fuel will scatter more muons. By placing detectors on either side of the reactor, one set to measure the incoming muon flux and the other to measure the angular distribution of the transmitted muons, one should be able to locate the heavy materials and deduce the state of the fuel assembly.



The measurement should be made with (mostly) horizontally-moving muons that cross through the vertically-standing fuel assembly, but few muons travel in a horizontal direction, and the low flux makes imaging problematic. So a team of Los Alamos researchers, led by physicist Cas Milner, built a mock reactor core (upper photo)— a tower of lead bricks surrounded by empty space and blocks of concrete. By looking at the horizontally-moving muons, and using newly developed algorithms, the team was able to reconstruct an image of the core (lower image).

Should the Japanese government request assistance in diagnosing the Daiichi power plant, Los Alamos will be able to respond quickly.

(Left) The Los Alamos National Laboratory acronym was the first radiograph made with electron radiography. Each letter is about 0.08 inches wide. (Right) The 1-inch wide "eRad" sign has letters less than 0.001 inch thick. The handwritten letters are visible because they were written with the Pilot Gold Metallic Marker, which contains 15–25 percent copper.

Super μTom

A particle source is not a problem for muon tomography, because muons—a middleweight version of the flyweight electron (the tau particle being the super heavyweight version)—are everywhere. They emerge from the aftermath of a collision between an atom and a cosmic ray, typically a very energetic proton, that against all odds slams into Earth's upper atmosphere after crossing more (possibly much more) than a trillion miles of space. About 10,000 muons hit a square meter of the Earth's surface every minute.

In the mid-1960s, Luis Alvarez—Berkeley physics professor, Nobel Laureate, and one of the proposers of the theory that it was a giant asteroid that did the dinosaurs in—built the first high-angular-resolution system that could detect the direction a muon was going as it entered his detector. He and his collaborators used this system to search for hidden chambers within the second-largest pyramid in Egypt, the Pyramid of Chephren.

Like electrons, muons are unaffected by the strong force that holds a nucleus together, although the charged muon does feel the electric field produced by the protons in the nucleus. The result is that if a muon passes close to a nucleus, it's likely to be deflected from its line of travel by a small amount (small angle scattering). The denser the material, the more deflections and the greater the scatter. On the flip side, if a muon travels some distance through a hidden room instead of solid rock, it deviates less from its initial trajectory.

"It worked," recalls Morris. "They were clearly able to see the outlines of the rock structure. They could even discern the six inches of limestone that remains on the pyramid's cap. Too bad they didn't see any hidden chambers."

Fast forward approximately forty years to a world that depends on the peta-scale movement of goods around the globe, and lives with the prospect of a terrorist group detonating some type of nuclear or dirty radiation bomb in a population. Heavy nuclei contain many protons and will redirect muons through larger deflection angles more often than will light nuclei. And hardly any material has more protons per nucleus than plutonium.

With an ever present, natural particle source, μTom can be set up anywhere in the world. On the other hand, the low natural muon flux (compared to an accelerator source as in pRad) limits the amount of information one can gather about the object in a reasonable amount of time. Thus, μTom makes no sexy radiographs showing clearly defined chunks of fissile material, but it provides enough information to identify material that should never enter this country.

Super Electrons?

Yet another type of radiography is being developed jointly by scientists at Los Alamos and the Idaho Accelerator Center. Electron radiography, or eRad, is ideal for imaging the interiors of thin objects (less than a few millimeters thick).

Scientists at Los Alamos are looking into employing eRad simultaneously with x-ray radiography in their proposed MaRIE facility. The goal for MaRIE is to obtain an unprecedented understanding of material behaviors within environments that range from the ordinary to the extreme, thus paving the way to develop the next-generation materials that will likely be needed to sustain society's technological growth.

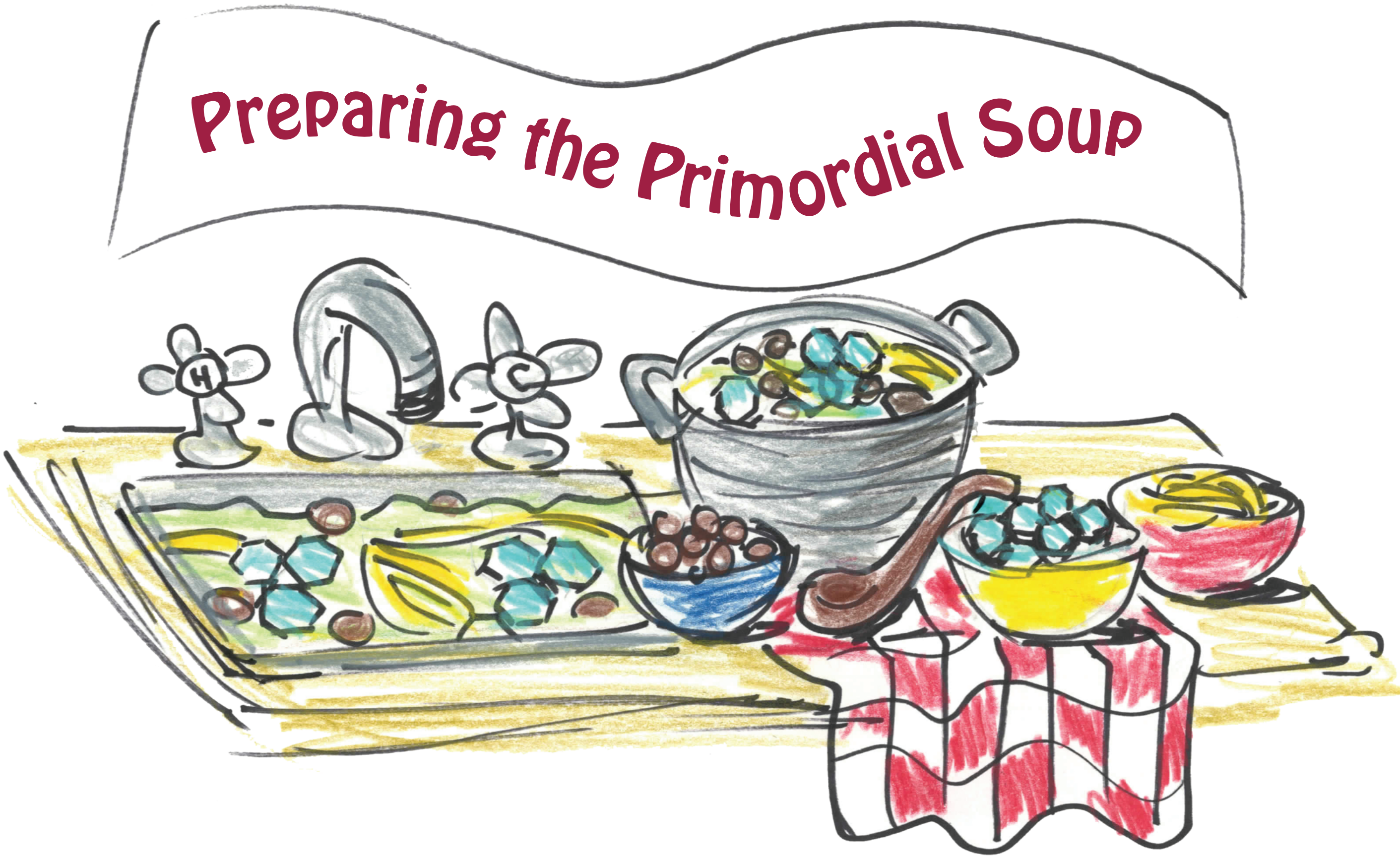
For a slab-like target, high-energy x-rays would pass through the wide dimension of the slab and provide information about micron-scale material properties, such as what happens to crystal domains or grain boundaries as the target is blown up, crushed by shock waves, or stressed in some other extreme manner. High-energy electrons would pass through the slab's thin dimension, providing information on surface properties or material interfaces.

"It's also possible to simultaneously probe the sample with pRad," says Frank Merrill, one of the developers of eRad. "That would allow us to observe how a severely-stressed material behaves over four orders of magnitude, from microns to centimeters, or over what is likely to be all relevant length scales."

Even if eRad isn't used at MaRIE, that will hardly dampen the enthusiasm of the ordinary, largely unacknowledged non-superheroes who, through mostly personal dedication, developed an extraordinary technology.

"If you think about it," says Saunders, "we developed pRad to address a need of the weapons community, and now it's being used to study unclassified, non-weapons-related objects. The knowledge gained from refining pRad was then used to turn muon tomography—developed for scientific reasons—into a viable means to screen cargo for special nuclear materials. Whichever side of the fence you're on, charged-particle radiography is a terrific example for how the pursuit of fundamental science can benefit society in unforeseen ways." Super rad, man! ❖ LDRD

—Jay Schecker



Primordial Soup

Ingredients:
One ocean of water
Sunlight (as available)
Organic materials from space: amino acids, fatty acids, polycyclic aromatic hydrocarbons, other hydrocarbons as neeed

Dissolve organic materials in ocean, let simmer in sunlight for up to a billion years. Makes large numbers of prebiotic cells.

The notion that the raw materials for life—perhaps even life itself—simply fell from the sky has been batted about for decades. In this view, organic matter—known to exist in interstellar clouds of gas and dust—was brought to Earth by asteroids, comets, stardust, or other cosmic bodies crashing into our young planet. The extraterrestrial influx of ready-made molecules could have seeded the barren world with the organic ingredients needed to get biology rolling.

Questionable? Perhaps. But one experiment answers a thousand questions, and now, Los Alamos chemists James Boncella and Jonathan Cape have shown that aqueous mixtures of organic molecules detected in outer space can arrange themselves into simple cell-like structures able to capture and store energy from the Sun—important steps in the prebiotic (before life) chemical pathway that led to the more complicated chemical systems associated with life on Earth.

A Marvelous Event

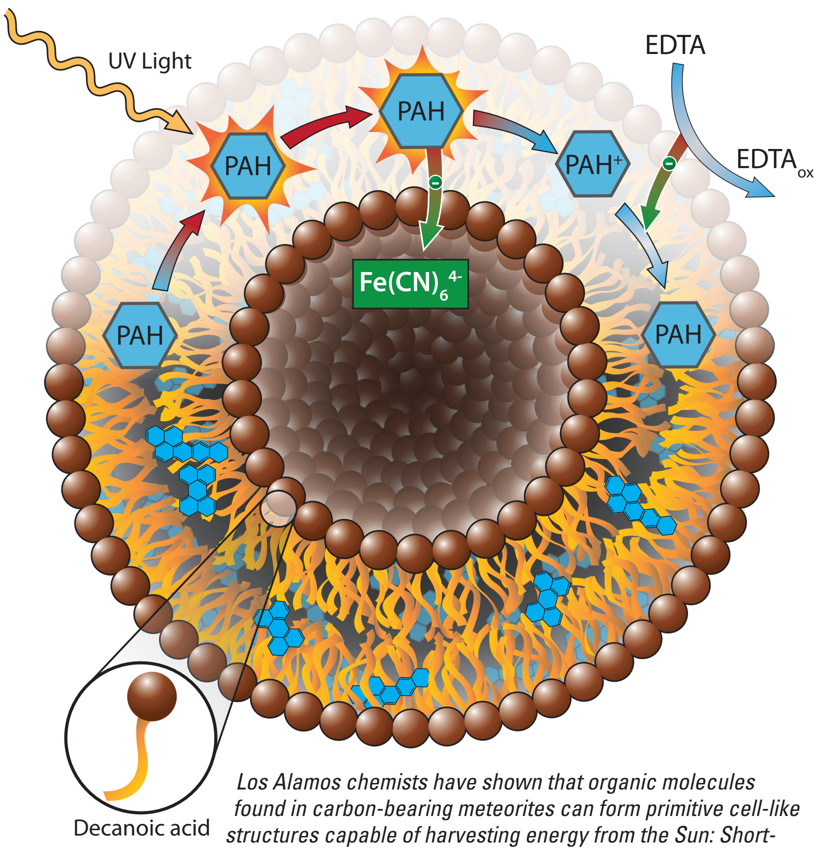
Extraterrestrial seeding gained prominence in 1969 with the fall of a meteorite (witnesses reported an exploding fireball) near the Australian village of Murchison. More than 100 kilograms of charcoal-colored fragments were collected, and early analyses revealed the presence of hydrocarbons and a number of common amino acids. Scientists have since concluded that the interiors of well-preserved fragments were unaltered by terrestrial contaminants, and many believe that the Murchison meteorite is a pristine relic from the early solar system.

Murchison (and other carbon-containing meteorites) harbored a cornucopia of complex organic molecules, including amino acids, an abundance of different fatty acids, and aromatic hydrocarbons (hydrocarbons containing at least one six-carbon-atom ring). Just last year, a team of European researchers used ultra-high-resolution mass spectrometry to uncover more than 14,000 unique molecular compositions in Murchison's organic extracts.

The wealth of the interstellar organics encouraged Boncella and Cape to explore the prebiotic possibilities. They joined with former Laboratory colleague Pierre-Alain Monnard, now at the University of Southern Denmark, to create and evaluate prebiotic structures made from the same organic molecules found within Murchison.

They began by fashioning primitive cell-like structures from mixtures of short-chain fatty acids, the most plentiful water-soluble organic compounds in the meteorite. The structures will form spontaneously in aqueous solutions because of the push-me-pull-you nature of the fatty acid—the "head" of the lollipop-shaped molecule mixes happily with water, the hydrocarbon tail doesn't. To shield their tails from water, a group of fatty acids will arrange themselves into double-walled, hollow vesicles, the heads forming the inner and outer wall surfaces, with the tails sandwiched between the two surfaces, sheltered from water.

The chemists found that, of the fatty acids found within Murchison, decanoic acid, with a ten carbon-atom tail, was the best vesicle former—its longer tail providing a greater hydrophobic driving force. They also found that vesicles formed more readily from messy mixtures of short-chain fatty acids than from single components, an intriguing discovery given the presumed complexity of the primordial soup.



Los Alamos chemists have shown that organic molecules found in carbon-bearing meteorites can form primitive cell-like structures capable of harvesting energy from the Sun: Short-chain fatty acids (brown and orange) self-assemble into double-walled vesicles. Light-sensitive PAH molecules (blue) become excited by ultraviolet light to a higher energy state, and one of its electrons hops to a dissolved ferricyanide anion encapsulated within, thus storing the energy as chemical potential. The PAH molecule then accepts an electron from an external reducing agent, completing the charge-transfer cycle.

Interestingly, the researchers showed that the tiny mixed-component vesicles—only about a hundred nanometers in diameter—are able to encapsulate large negatively charged compounds, such as the electron-grabbing ferricyanide, a common laboratory oxidant. Held in solution inside the interior vesicle volume, the compounds are effectively segregated from the external environment. This act of containment, or compartmentalization, is a key characteristic of living cells and is thought to have arisen before life itself.

Energy Transfer

Boncella and Cape were also able to create fatty-acid vesicles exhibiting a rudimentary form of metabolism—the ability to capture and store energy for chemical transformations. The key insight was to include light-sensitive polycyclic aromatic hydrocarbons (PAHs) in the model system. Shaped like chicken-wire cutouts, PAHs are flat molecules made of fused carbon rings saturated with hydrogen atoms. PAHs are abundant in the Murchison meteorite and throughout the interstellar medium. They are also completely hydrophobic, so when added to premade vesicle solutions, PAHs migrate to the interior of vesicle walls, mingling with their fellow hydrophobes, the fatty-acid tails.

The membrane-bound PAHs serve, in essence, as solar spark plugs, initiating the conversion of the Sun's energy into stored chemical potential. The process begins with ultraviolet light exciting an electron in a PAH to a higher energy state—just the boost the electron needs to move across the inner vesicle wall and transfer to an encapsulated ferricyanide ion. The PAH becomes a positively charged radical, but returns to its original state after it accepts an electron from a reducing agent in solution outside the vesicle. The process is therefore repeatable. So energy (from the Sun) was transferred (by an electron) across the vesicle membrane and used to reduce an ion (ferricyanide)—a very simple metabolic-like sequence of events.

While their prebiotic chemical model shares fundamental attributes with living things, Boncella and Cape point out that they cannot know for sure whether they are on the right track. No physical evidence of prebiotic structures exists, so scientists may never know for certain what they looked like or how they functioned. But the lack of a fossil record also elevates the importance of laboratory experiments. "We can only speculate," says Boncella, "and then head into the lab to see what is plausible."

—Craig Carmer and Jay Schecker

SPOTLIGHT

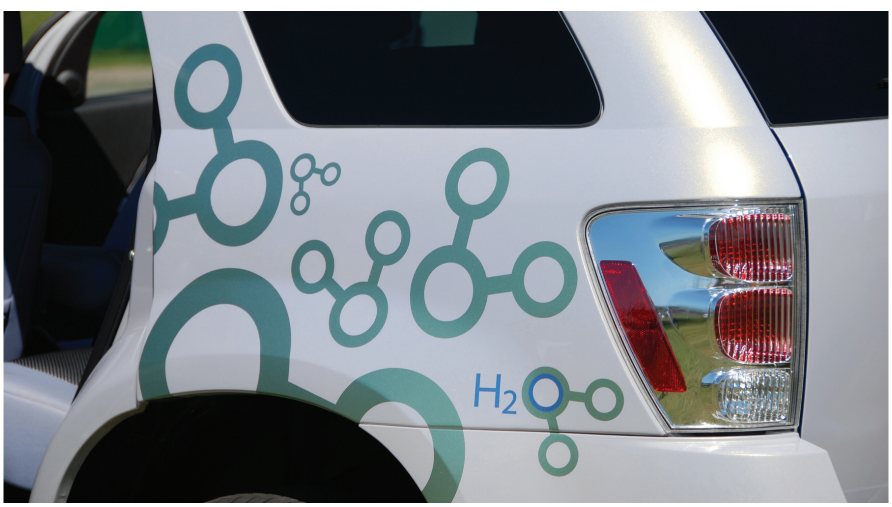
The (Lightweight) Heavy Hitter

Los Alamos chemist Andrew Sutton discovered a new method for refueling cars that could go the distance. Sutton revealed a novel single-stage method for recharging hydrogen-rich ammonia borane (AB), a potential onboard hydrogen-storage compound for fuel-cell-powered vehicles.

A fuel cell converts hydrogen in the presence of oxygen into electricity and water, and can do so efficiently without generating polluting emissions—the sole byproduct is water. Hydrogen is a common fuel used in fuel cells and provides substantial energy for its low weight, but it requires energy to produce and takes up a lot of space. In addition, it is dangerous to transport due to its explosive nature. Therefore, a material that can store and release hydrogen safely would be very attractive.

How do you store hydrogen? Transport and storage of hydrogen can be dangerous in pure form, but when hydrogen is stored as AB, it is thermally stable at ambient temperatures and is easily transportable. AB is a particularly attractive hydrogen storage material because it is nontoxic and can liberate large quantities of hydrogen, potentially enough to propel hydrogen-fueled vehicles 300 or more miles per "tank," a federal research goal. The challenges to this goal include controlled dehydrogenation—getting the energy out—and regeneration of the spent fuel.

In an ideal AB-based fuel cell, the hydrogen-depleted spent fuel residue is composed of polyborazylene (PB). Thermodynamically, there is no way to convert the PB back into AB using hydrogen directly. A Los Alamos team led by Ben Davis developed a method to recycle PB with minimal energy input by introducing tin hydride as a reductant—providing hydrogen to the spent PB. First, the spent fuel is "digested" with a thiol, then a tin hydride is added, followed by the addition of ammonia, which reproduces AB. This is a huge breakthrough in itself, but unfortunately, tin hydride would be too expensive to implement on a large scale due to the high costs of handling it.



Fuel-cell-powered cars such as this Chevrolet use hydrogen and oxygen to power the vehicle's electric motor, and the only emission is water. Los Alamos researchers have discovered a way to recycle the spent fuel.

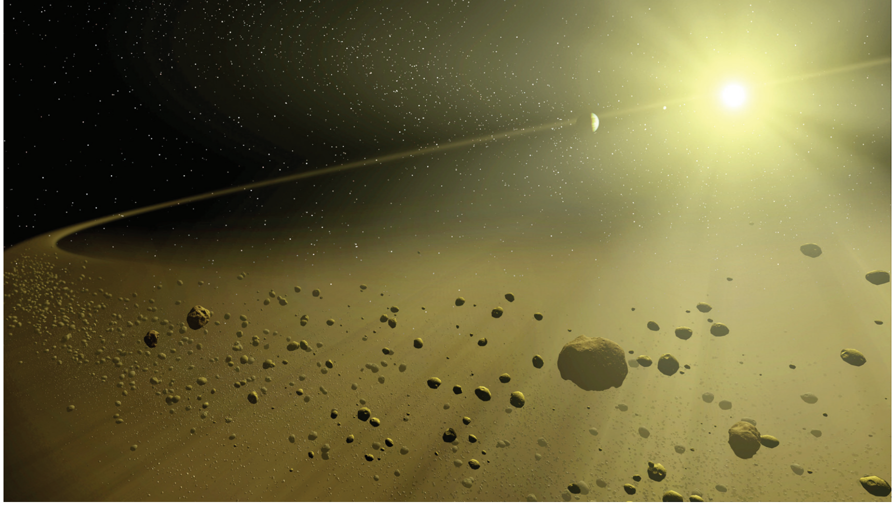
Carrying this work forward, Sutton decided to investigate a much lighter reductant in the form of hydrazine. He added hydrazine in liquid ammonia to PB, resulting in AB (the hydrogen source) and nitrogen. That is, he was able to devise a simple method to regenerate the hydrogen-storing compound from its spent-fuel form in a single container with just one step. Regeneration takes place offboard, but the researchers envision vehicles with interchangeable hydrogen storage tanks that can be swapped as needed.

The next target is to efficiently make hydrazine, as current manufacturing methods for hydrazine use energetically expensive precursors. Hydrazine is also potentially hazardous to transport across the nation in large loads, so Los Alamos researchers anticipate making it on-site during the AB recycling process by combining the byproduct nitrogen with hydrogen to make new AB. This is not a trivial process, but if hydrazine synthesis can be refined, the use of AB in the transportation sector could become viable. The achievements by Sutton and Davis greatly improve the characteristics of AB as a hydrogen storage material, potentially facilitating the large-scale implementation of hydrogen fuel cells that provide safe, renewable energy.

—Kirsten Fox

Solar System Surprise

During two years in interplanetary space, a NASA spacecraft called Genesis collected particles from the solar wind. Its purpose was to capture these atoms from the Sun and return them to Earth, where scientists would determine the solar abundances of various stable isotopes of nitrogen and oxygen, as well as other elements. These solar abundances can also be thought of as solar *system* abundances, since the Sun and planets all formed from the same cloud of matter and most of their combined mass resides in the Sun. The mission to



Early in the history of our solar system, the matter that would eventually form planets and other bodies acquired slight differences from the solar system's original chemical composition.

determine these abundances might have been a complete success if the spacecraft's parachutes hadn't failed during re-entry, causing the solar wind collectors to shatter upon impact with the ground.

Fortunately, in addition to the passive collectors, the Genesis capsule contained an instrument, designed by Los Alamos's Jane Nordholt, Roger Wiens, Ronald Moses, and Steven Storms, that concentrated solar wind particles onto a small target. The target managed to survive the crash, thanks to its strong mechanical design. (Wiens describes Genesis as "the biggest comeback mission since Apollo 13.") The surviving target was analyzed for the abundances of three isotopes of oxygen—^{16}O, ^{17}O, and ^{18}O—and two isotopes of nitrogen—^{14}N and ^{15}N—in order to compare the solar system concentrations of these isotopes to those found here on Earth. As it turns out, relative to the bulk of the solar system, our planet appears to be an anomaly.

In terms of mass, oxygen is by far the most abundant element in the inner solar system planets, Mercury through Mars, and ^{16}O is by far its most abundant isotope. Samples from the Earth, Moon, Mars, and meteorites generally share the same abundances of all the stable oxygen isotopes, but the Genesis solar wind samples revealed 7 percent less ^{17}O and ^{18}O (relative to ^{16}O) than what has been found in these inner solar system samples. That is, the abundance ratios of both $^{17}O/^{16}O$ and $^{18}O/^{16}O$ were 7 percent smaller in the solar wind. It follows that whatever caused the 7-percent enrichment of these two isotopes in the inner solar system bodies relative to the Sun operated on both isotopes in the same way, even though their masses differ. One possibility, known as photochemical self-shielding, would have operated when the solar system was very young, as molecules of carbon monoxide (CO, the most abundant oxygen-bearing gas at the time) were broken up by intense ultraviolet radiation from the young Sun. Wavelengths most efficient at breaking up $C^{16}O$ were consumed relatively close to the Sun, due to the much greater abundance of the ^{16}O isotope. Wavelengths efficient at breaking up $C^{17}O$ and $C^{18}O$ traveled farther out into the planet-forming region, freeing up an excess of the heavier oxygen isotopes for incorporation into planets.

The Genesis crash site in Utah.
CREDIT: NASA/JOHNSON SPACE CENTER.

The Genesis results for nitrogen were similarly enlightening. The team found 38 percent less ^{15}N (relative to the much more common ^{14}N) in the solar wind than is found in Earth's atmosphere. The same photochemical self-shielding effect could be responsible for this deficiency, with solar ultraviolet light selectively breaking up the molecule N_2 rather than CO in this case. However, with only two stable isotopes of nitrogen, evidence for its self-shielding is less conclusive than it is for oxygen. Other nitrogen samples from the solar system include meteorites, which come from relatively nearby in the inner solar system and have a similar isotope composition to the Earth, and comets, which come from the outer solar system, beyond the planets, and have more than double the $^{15}N/^{14}N$ ratio found on Earth. Taken together with the Genesis data, these results suggest that rocky, inner solar system bodies like the Earth had multiple sources of nitrogen: Some was primordial, like the solar wind composition, and some was enriched in ^{15}N, like cometary composition. The mixture of these two sources led to an isotope ratio in between the two. Indeed, it is known that the planets were bombarded by comets in the past. However, Jupiter's nitrogen ratio matches that of the Sun. Thus, the Genesis results imply a mystery as to why the terrestrial planets' nitrogen was strongly influenced, either by comets or photochemical self-shielding, while Jupiter remained largely unaffected.

The measured abundances from Genesis validate the predictions of the photochemical self-shielding theory, at least for oxygen, but they also point researchers toward new mysteries to investigate, such as the cometary enrichment history of Earth, Jupiter, and other solar system bodies. In this sense, the Genesis experiment provided the best of both worlds, answering some questions and raising others—not too shabby for a spacecraft that suffered a terminal-velocity crash in the desert.

—Craig Tyler

Reaction to Fukushima

On March 11, a devastating earthquake hit Japan and triggered a massive tsunami that left a wake of destruction, including major damage to the Fukushima Daiichi nuclear power plant. The aging plant consisted of six boiling-water reactors powering electrical generators. The 45-foot waves halted power and disabled a number of reactor cooling systems, leading to nuclear radiation leaks, hydrogen explosions, and most likely, significant core melting. Radiological contamination ensued and Japan mandated a 12.5-mile-radius exclusion zone around the plant.

In response to the radioactive iodine emanating from the power plant, the Japanese government tested water from various cities across its nation and announced that the level of radioactivity exceeded legal limits. Around the world, people feared another Chernobyl—the 1986 reactor explosion that spread carcinogens across Eastern Europe, killed thousands, and left towns uninhabitable—and they needed answers quickly. Los Alamos scientists, experts in nuclear reactions, heeded the call.

During the first several weeks following the earthquake, the U.S. Department of Energy (DOE) provided analysis to support the response to events at the Daiichi plant. This support involved a broad set of institutions with more than 200 people contributing. The DOE sought help from Los Alamos, as it did previously for the Three Mile Island and Chernobyl incidents, on issues related to materials, health physics, nonproliferation safeguards, and reactor design. Dozens of experts in electrical power restoration, cooling systems, nuclear and radiochemistry, spent fuel pools, and robotics provided near- and long-term support to Japan.

Tsunami waves approach the Number 5 reactor of the Daiichi nuclear power plant in Fukushima, Japan on March 11.
CREDIT: TOKYO ELECTRIC POWER COMPANY

Los Alamos teams characterized and modeled events during the nuclear accident, hoping to learn more about the safety of reactor cores while simultaneously providing insight to mitigate potential similar events on U.S. soil. Researchers provided technical perspectives regarding hydrogen explosion avoidance, burn-up calculations for isotope release, fission product calculations for coolant systems and worker exposure predictions, corrosion perspectives, heat-transfer analysis, criticality, and methods to decontaminate water. To verify data, Los Alamos colleagues also peer-reviewed calculations performed externally. Additionally, Los Alamos scientist Cas Milner proposed to Japan a technique called muon scattering tomography to help locate and quantify nuclear material. Milner's team constructed a mock reactor in Los Alamos and successfully demonstrated how the technique depicts where the uranium fuel resides within the reactors. [See "Dial μ for Assistance" on page 22 for more on this effort.]

Los Alamos air specialist Michael McNaughton and colleagues quickly deployed high-volume air samplers to see if radioactive emissions from Japan could be detected in Los Alamos, New Mexico. Detectors in Los Alamos picked up traces of radioactive iodine and cesium, among other isotopes. Levels were higher than those detected after the Three Mile Island incident, but lower than Chernobyl, McNaughton said.

What is the real risk of this type of disaster happening again? Have we appropriately quantified the risk to our own citizens? It's hard to be certain. However, Los Alamos researchers have helped to mitigate the risk by proposing rigorous new regulations to the Nuclear Regulatory Commission (NRC). The accident in Japan was caused by a combination of extraordinary natural forces far more severe than the Fukushima Daiichi plant was designed to accommodate, according to the NRC. Fortunately, as Los Alamos nuclear engineer David Dixon points out, "New reactors address a lot of the problems."

—Kirsten Fox

Greenhouse Gang

The Department of Energy's (DOE) Los Alamos, Lawrence Livermore, and Sandia national laboratories, together with NASA's Jet Propulsion Laboratory, have joined together to address the increasing need to monitor and analyze the emission of greenhouse gases around the world. Program leaders from the multi-lab team—affectionately known as the "gang of four"—envision a network of sensors to measure the greenhouse gas emissions, and computers to calculate how the emitted gases will move about. The resulting greenhouse gas information system, or GHGIS, would enable policymakers to verify compliance with international treaties aimed at controlling emissions. GHGIS data could also support future carbon control initiatives, such as cap-and-trade.

Sounds good, but the gang faces a number of obstacles before the system becomes a reality. For one, the measurements themselves must be very sophisticated. Normal fluctuations in the amount of atmospheric carbon dioxide—the primary greenhouse gas—from natural sources exceeds the amount discharged by human activity by a factor of 20, so properly identifying who, if anyone, is responsible for the emissions is far from simple. Then there's the hardware involved: the sensor platforms will need to include instrumentation in the air, land, sea, and

space—all of which must be integrated to yield a single coherent picture.

In order to credibly attribute the measured emissions to their sources, data will need to be combined and reconciled with reported fossil fuel use. Fuel inventory figures for electrical power production and transportation will be blended with various energy use and economic data. All this data, both measured and reported, will be fed into a computer model for analysis, and any attributable emissions will require an associated estimate of their uncertainties. (The sources of those uncertainties may range from direct measurement errors to optimistically massaged economic figures.) Finally, the model will have to account for all the factors that influence the movement of greenhouse gases, such as ocean transport, agricultural activity, and the background carbon cycle.

It should be possible to overcome all of these challenges, but doing so will require the cooperation of a wide range of institutions and agencies, including government and private sector. The gang of four has already completed its first objective, defining the requirements of the system and figuring out what will be needed in order to meet those requirements, and has recruited three more DOE laboratories to participate: the Oak Ridge, Lawrence Berkeley, and Pacific Northwest national laboratories. One day, this broad collaboration expects to produce a periodic report that quantifies greenhouse gas emissions and identifies their sources on a world map.

But won't that day be delayed by the logistical challenges associated with collaborating between seven national laboratories? Karl Jonietz, head of the GHGIS project at Los Alamos, doesn't think so. "For a program this far-reaching, we need all these laboratories to work together," he says. "No one lab could do it in the time required."

—Craig Tyler

Solvay Centennial

In October of 1911, top physicists of their day gathered in Brussels for a conference on "The Theory of Radiation and Quanta"—one of the earliest and most productive meetings in the emerging field of quantum physics. The meeting, initiated by Belgian industrialist Ernest Solvay and known as the Solvay Conference on Physics, included such giants of modern physics as Max Planck, Louis DeBroglie, Marie Skłodowska-Curie, Ernest Rutherford, Hendrik Lorentz, and Albert Einstein. Their discussions centered around the roles of the classical and quantum approaches to understanding nature.

One century later, in October of 2011, leading quantum physicists gathered again in Brussels for a new Solvay conference entitled, "The Theory of the Quantum World." Los Alamos's Wojciech Zurek was invited to attend. Zurek is best known for his pioneering work on quantum decoherence, the mechanism by which quantum systems become effectively classical as the information about their states "leaks" out and affects their environment. He is also known for co-authoring the famous quantum "no-cloning" theorem and for his recent work on quantum discord, which essentially describes how extensively a quantum system is disturbed when one of its properties is measured. Zurek was honored to be among only 72 invitees—many of them Nobel Prize winners, like many of the participants at the original Solvay conference. [Look for more on Zurek's work on quantum discord to be featured in an upcoming issue of *1663*.]

—Craig Tyler

LA

THÉORIE DU RAYONNEMENT

ET LES QUANTA.

RAPPORTS ET DISCUSSIONS

DE LA

Réunion tenue à Bruxelles, du 30 octobre au 3 novembre 1911.

SOUS LES AUSPICES DE M. E. SOLVAY.

Publiés par MM. P. LANGEVIN et M. de BROGLIE.

Many of the giants of twentieth-century physics appear in this group photo from the first Solvay Conference on Physics in 1911. Inset: Part of the invitation to the first Solvay conference.
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A coyote near Pilar, New Mexico, pauses as if to say, "You have three seconds to take your photo and then I'm gone!"

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